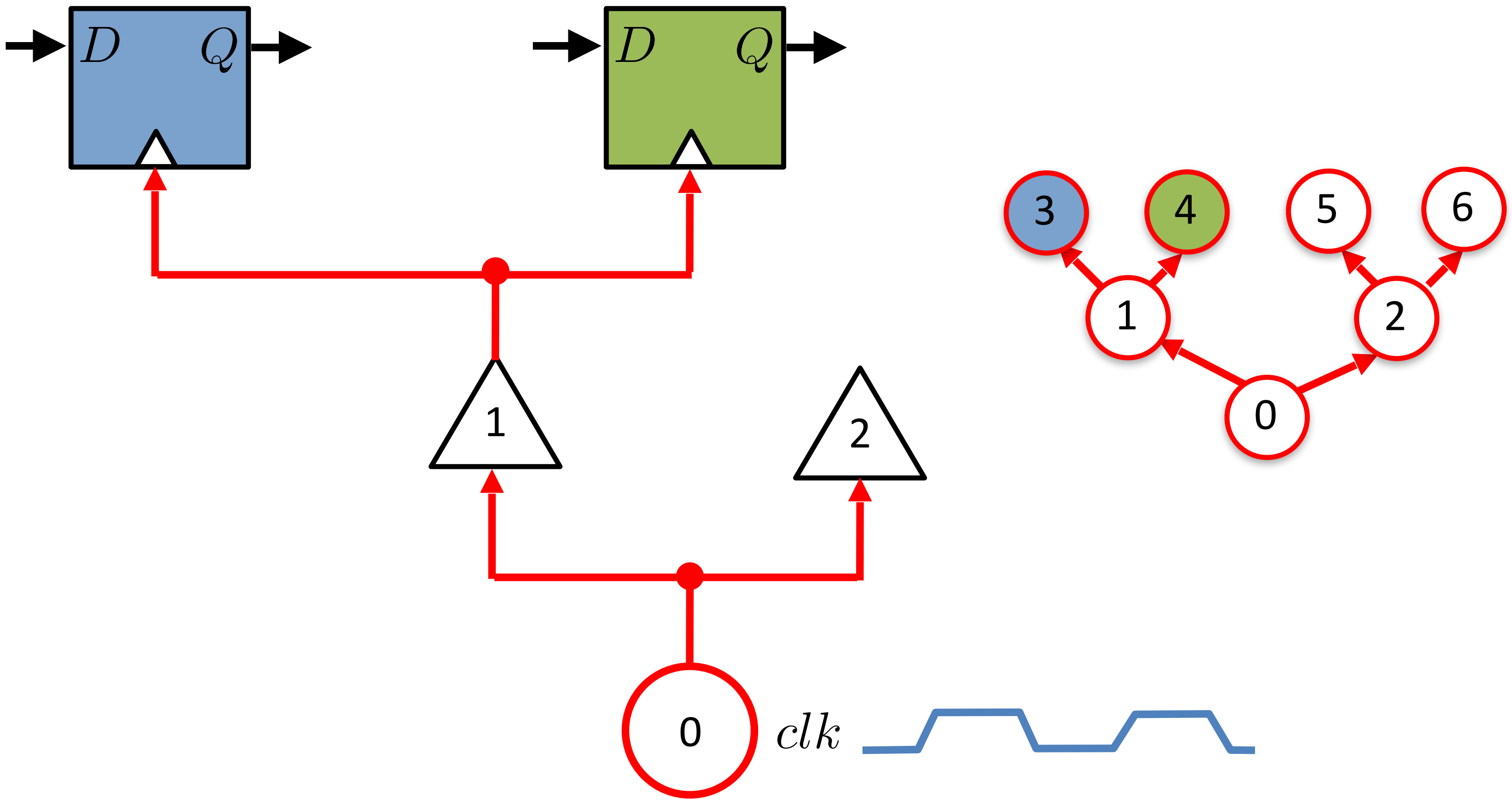
Chapter 11

Low-degree clock distribution networks

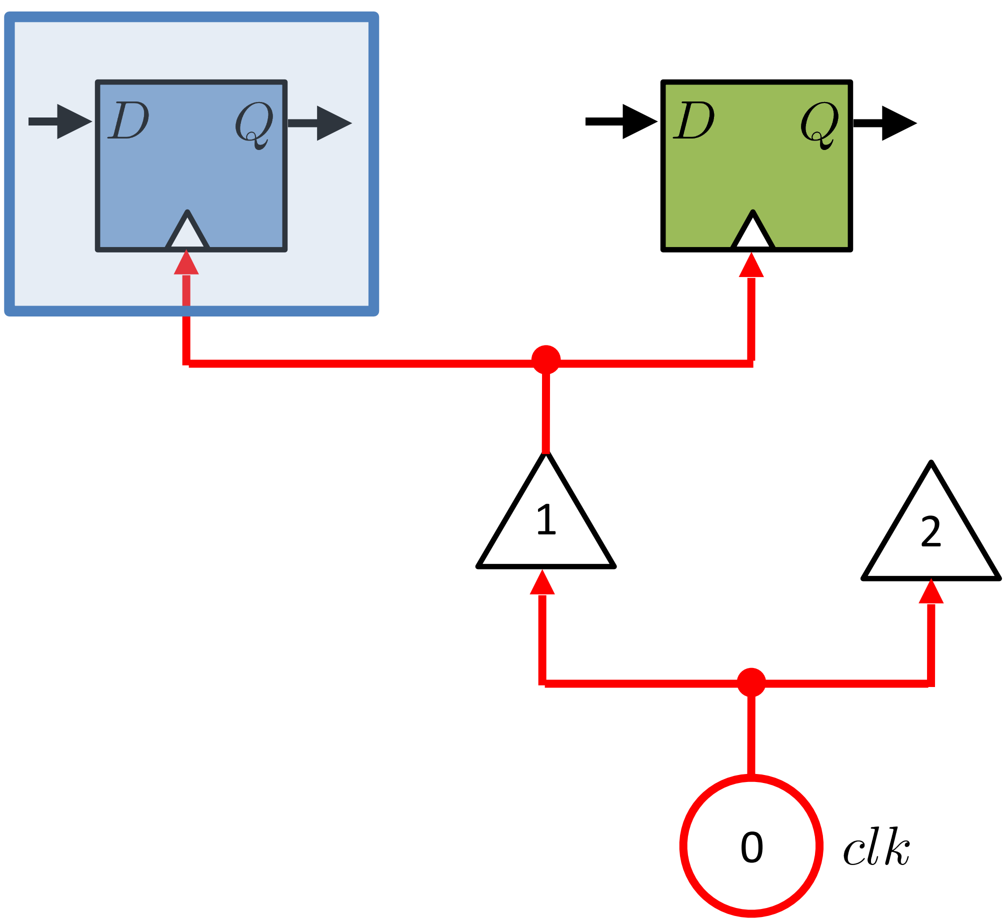
Matthias Fuegger and Christoph Lenzen

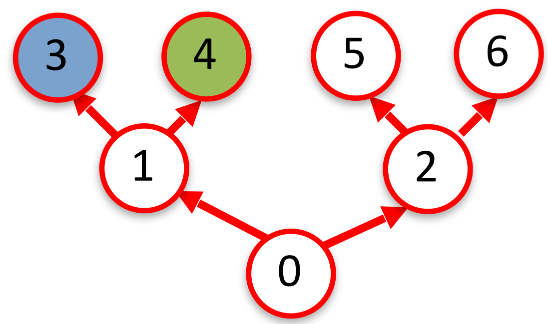
Clock distribution network



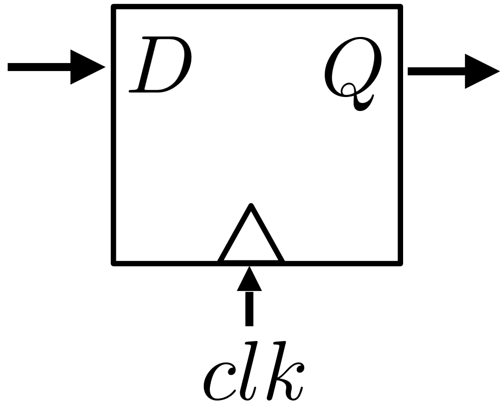
Quick summary...

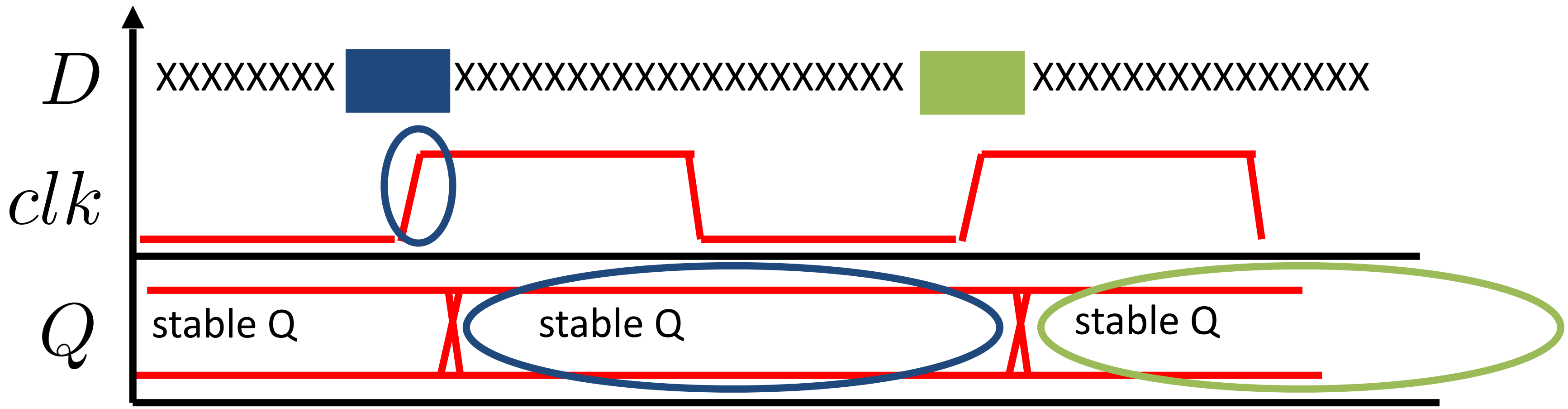
Clock distribution network



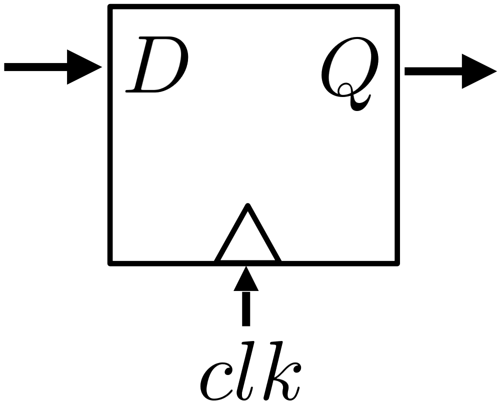


Flip-flop = edge triggered copy



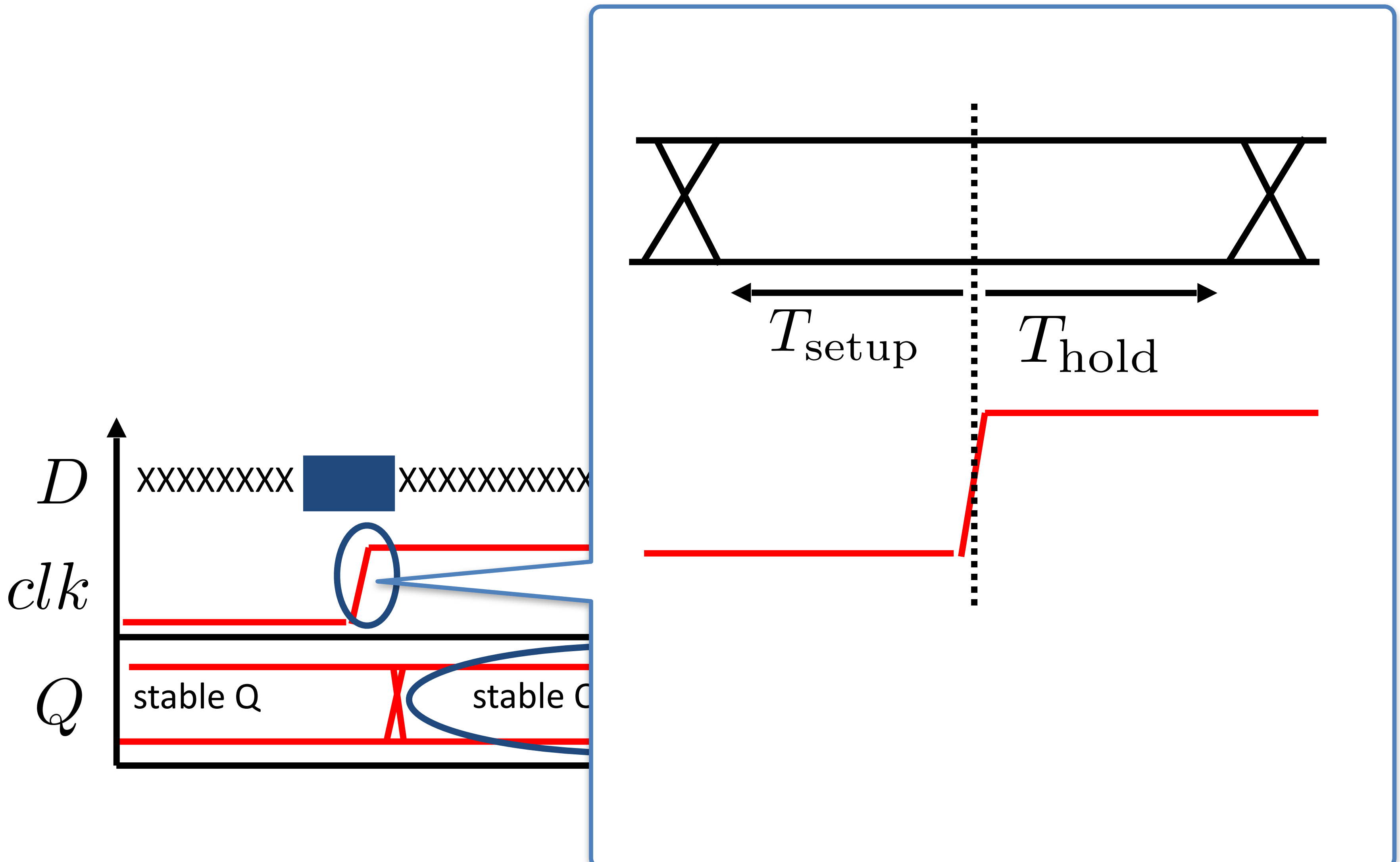


Flip-flop = edge triggered copy

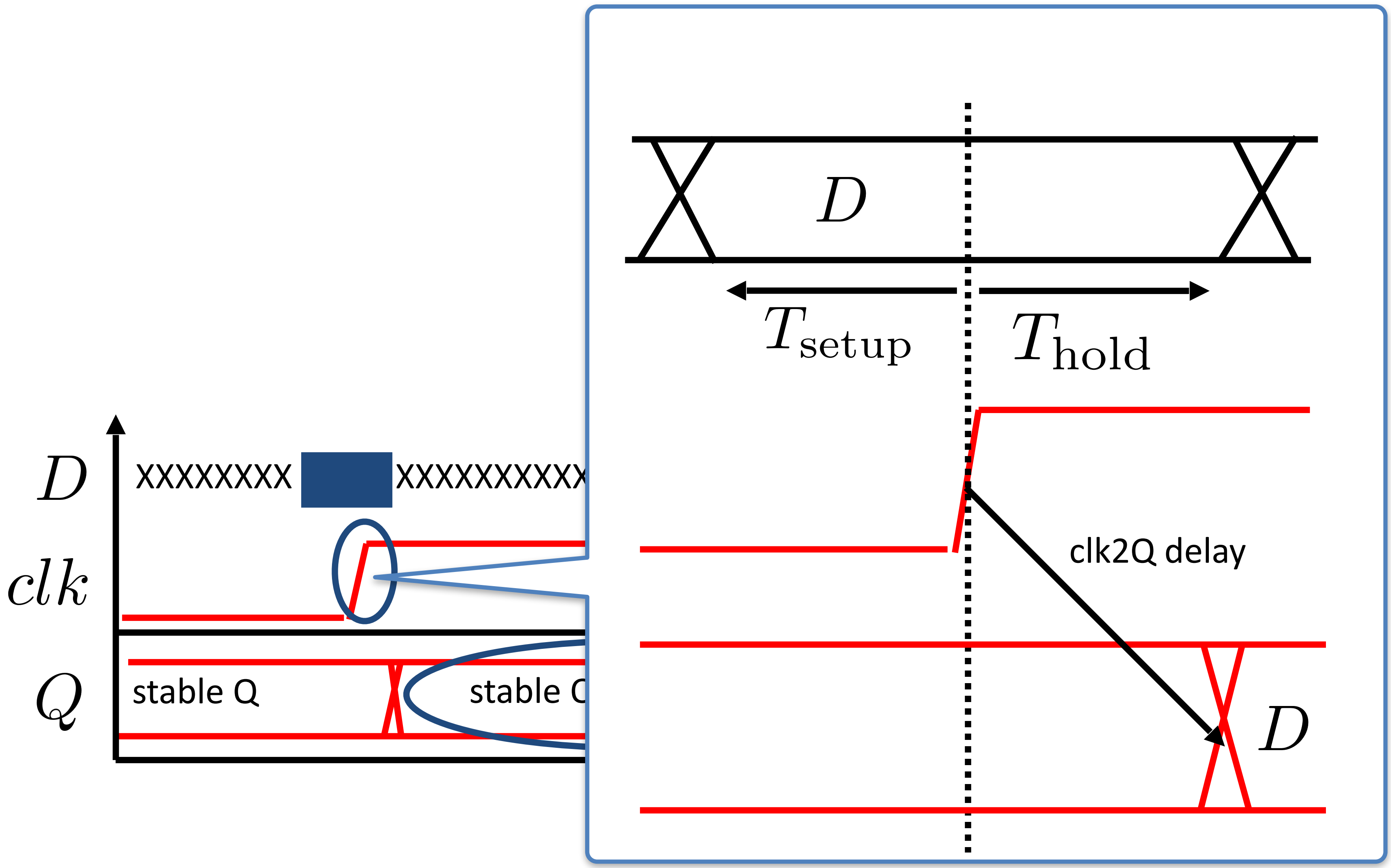



```
-- FF
FF: process (clk, D)
begin
    if (clk'event and clk = '1') then
        Q <= D;
    end if;
end process FF;
```

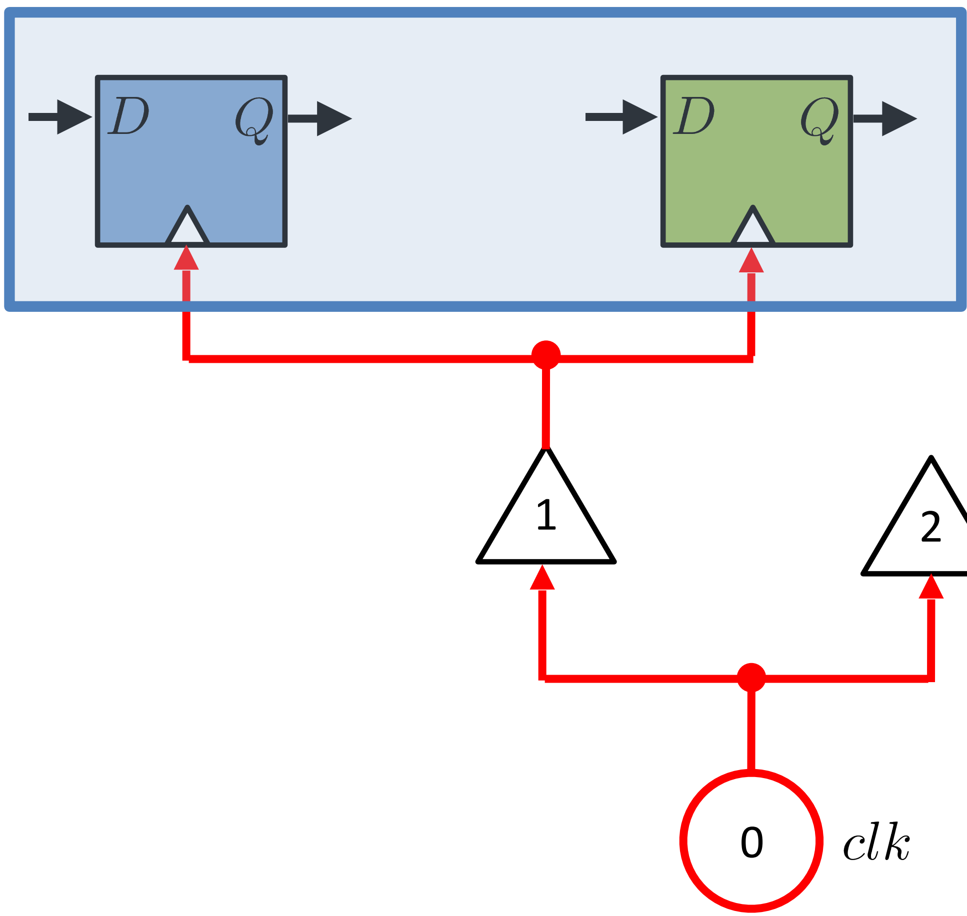
Timing: constraints

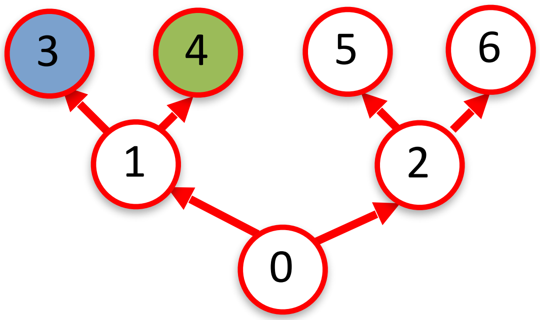


Timing: guarantees

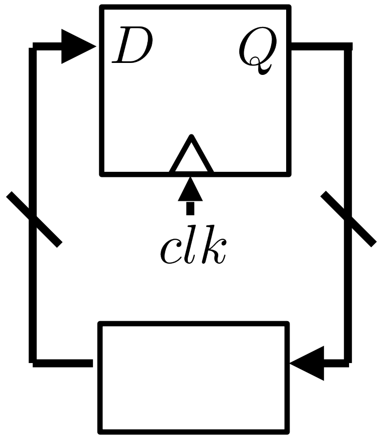


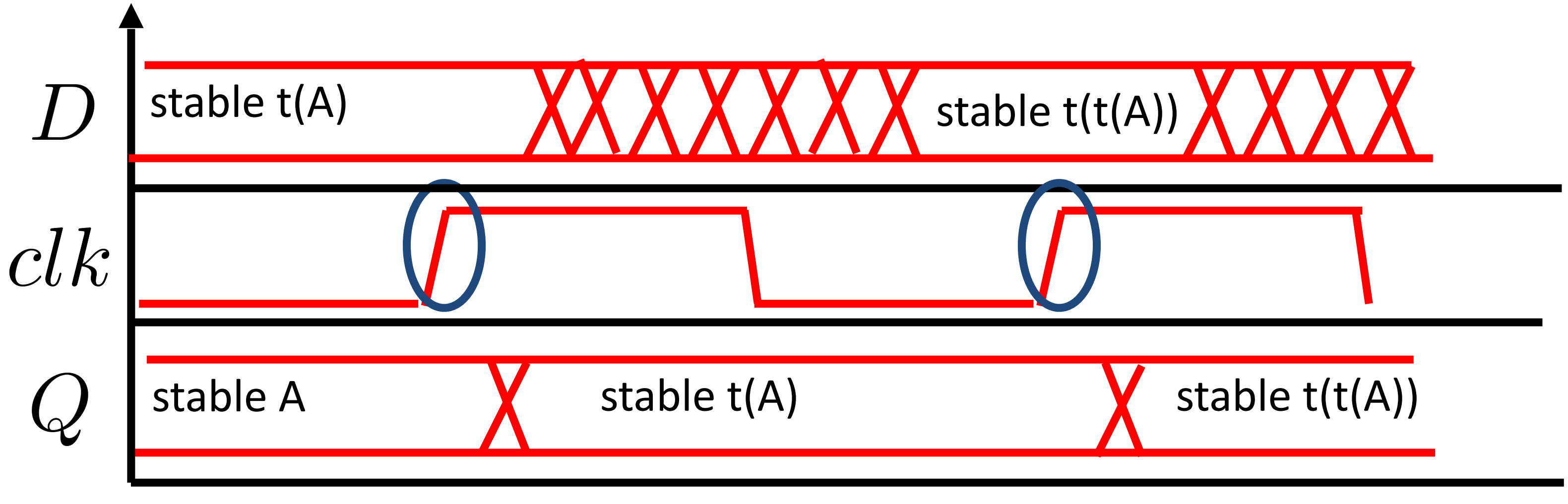
Goal: small skew

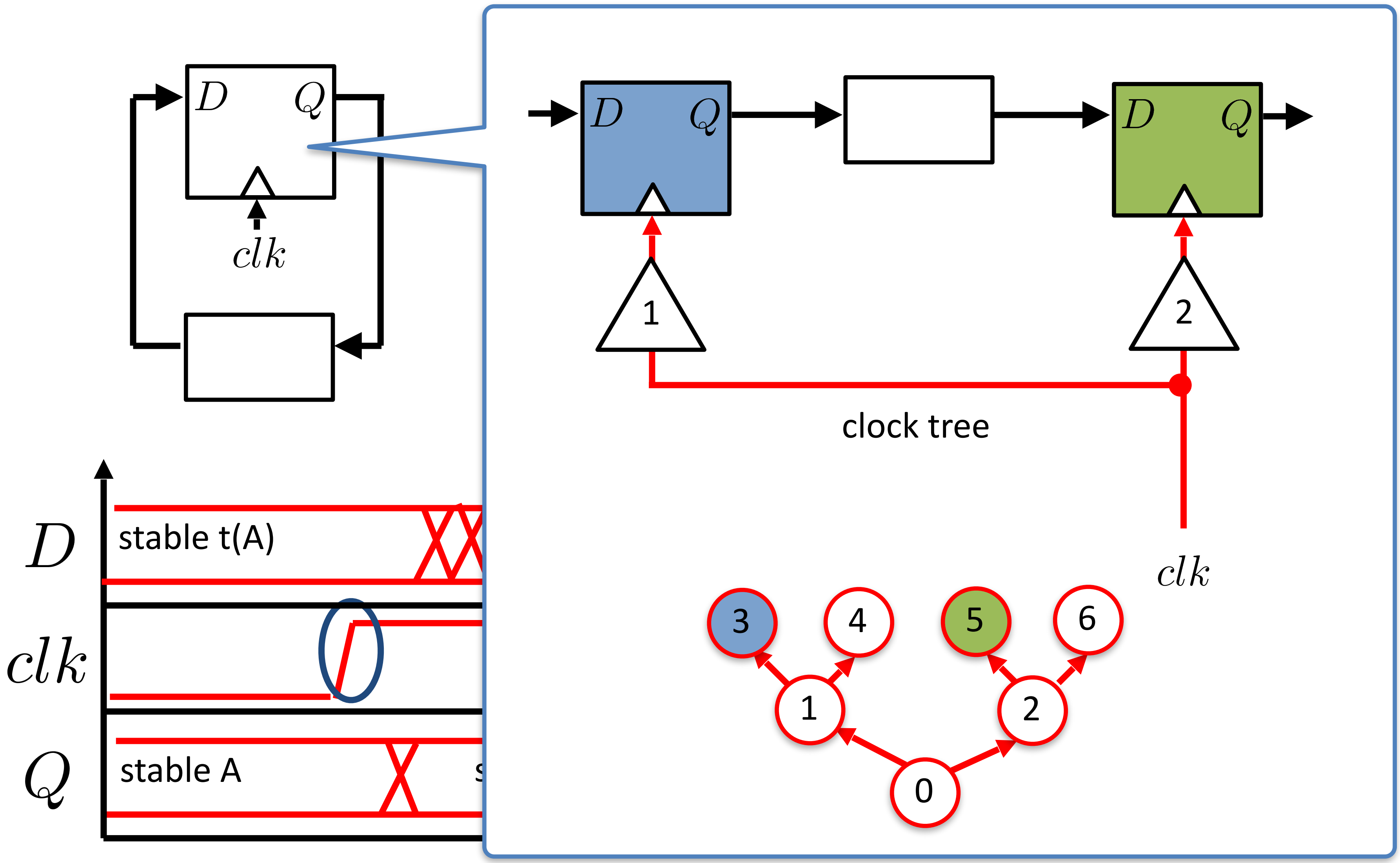




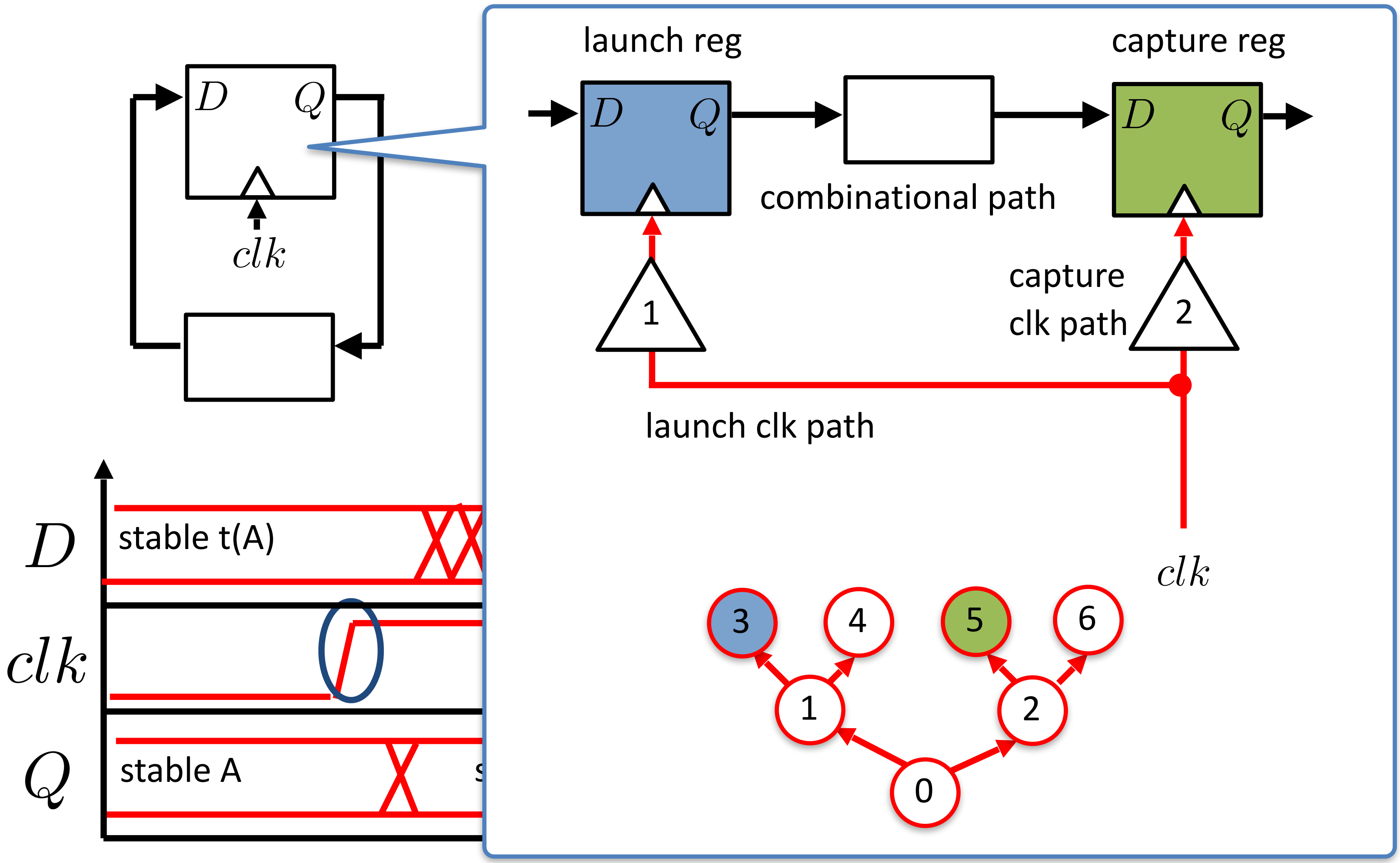
Clocked Design



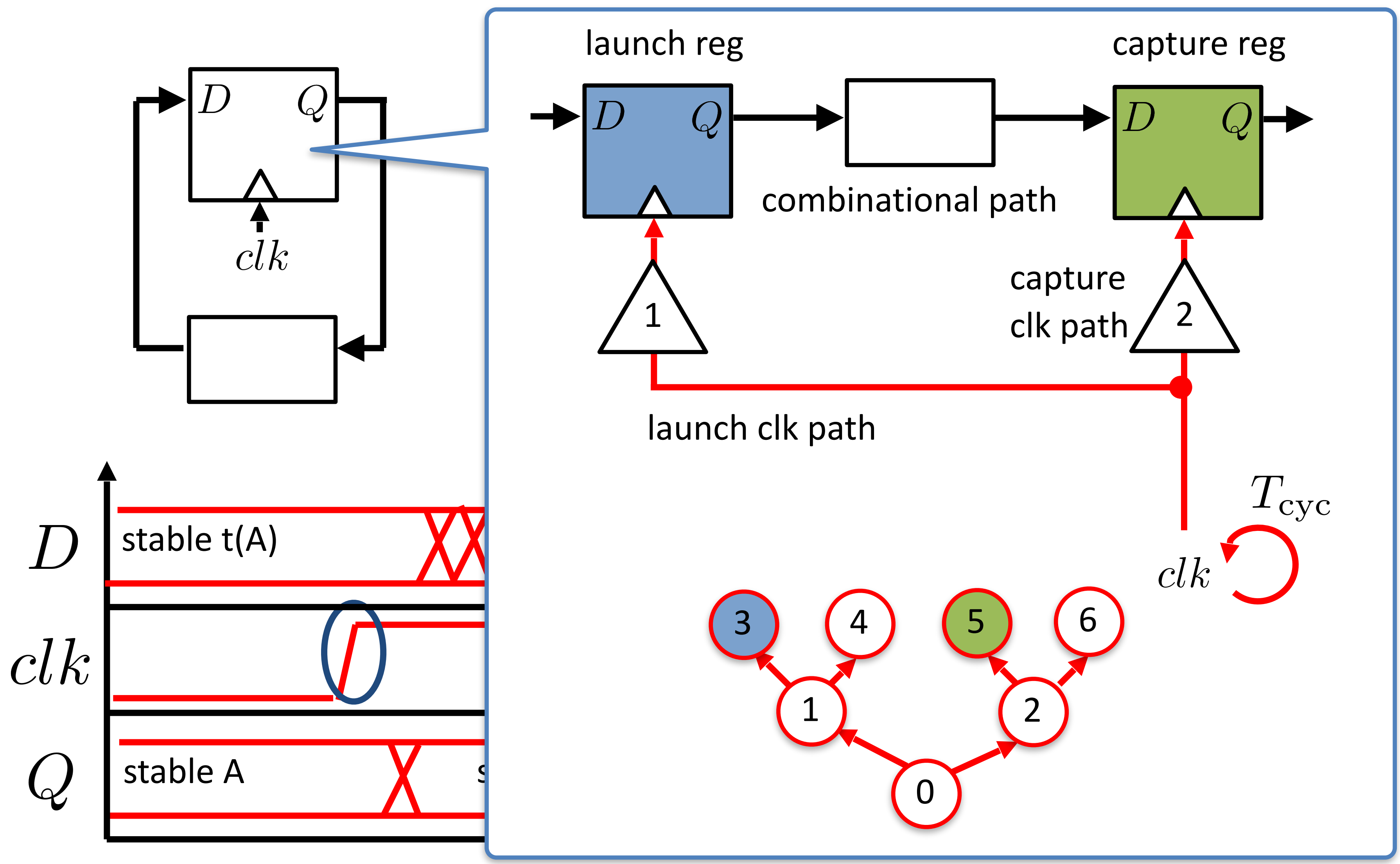




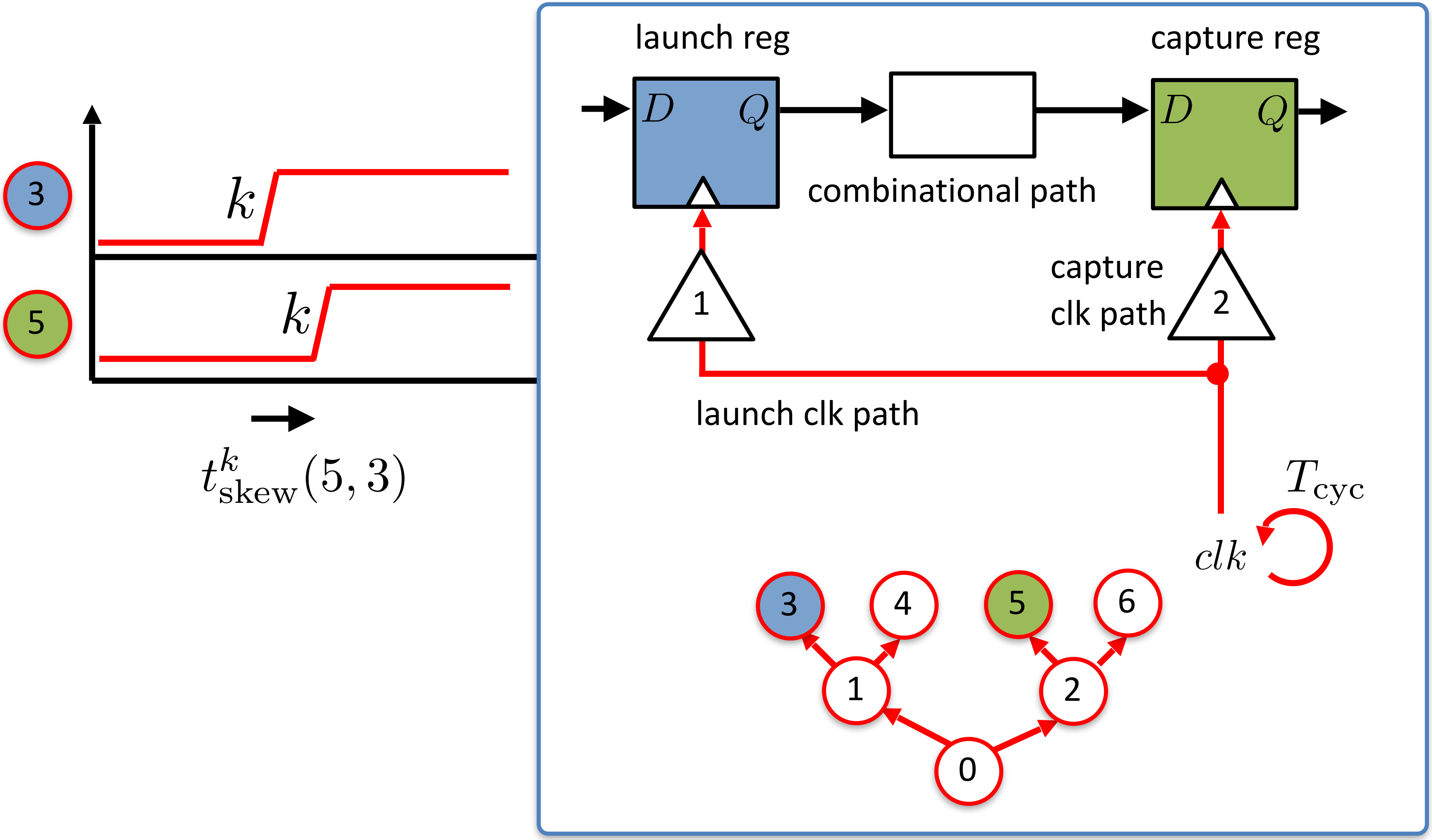
D
Q
clk
D
stable t(A)
clk
Q
stable A
D
Q
D
Q
1
2
clock tree
clk
3
4
5
6
1
2
0

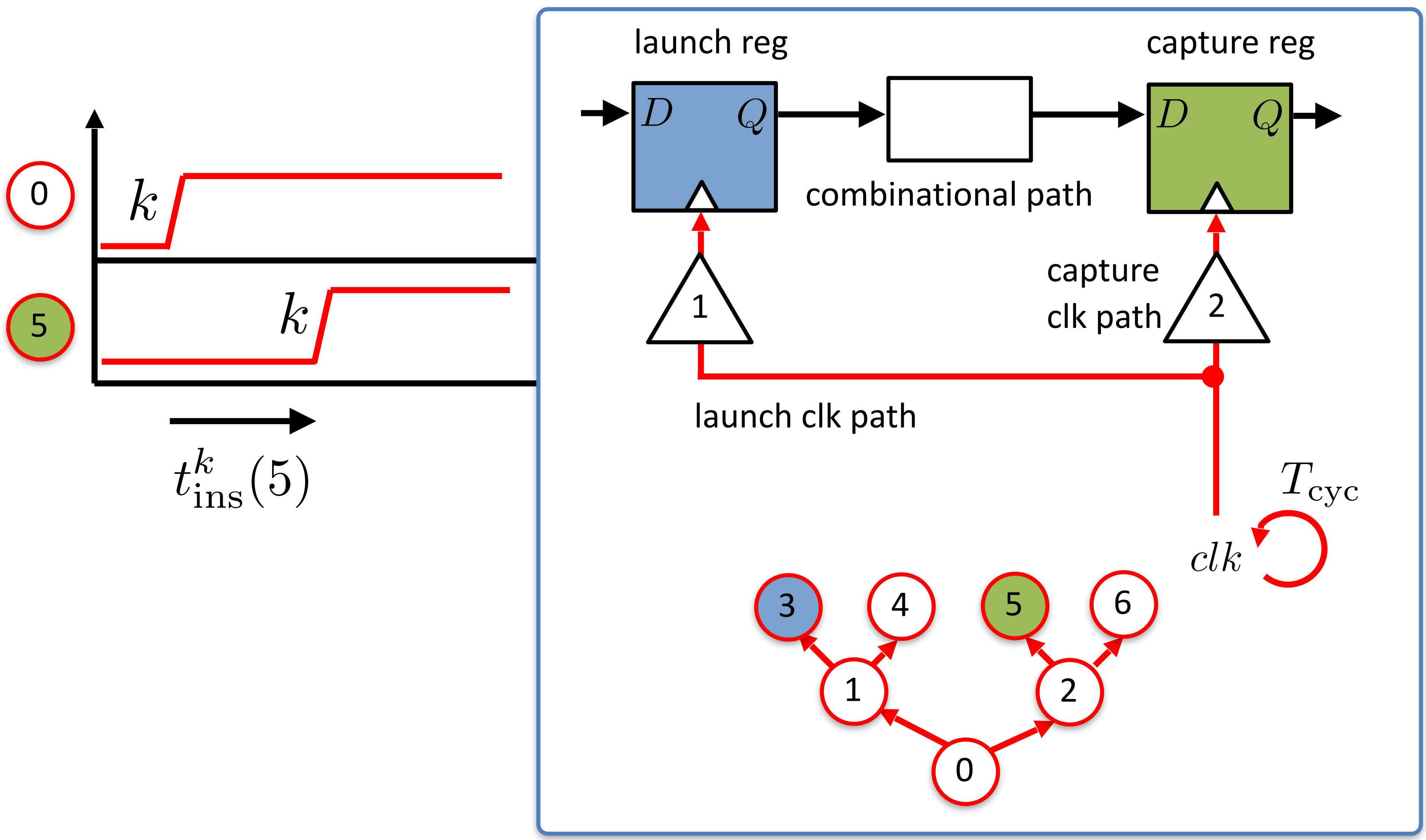


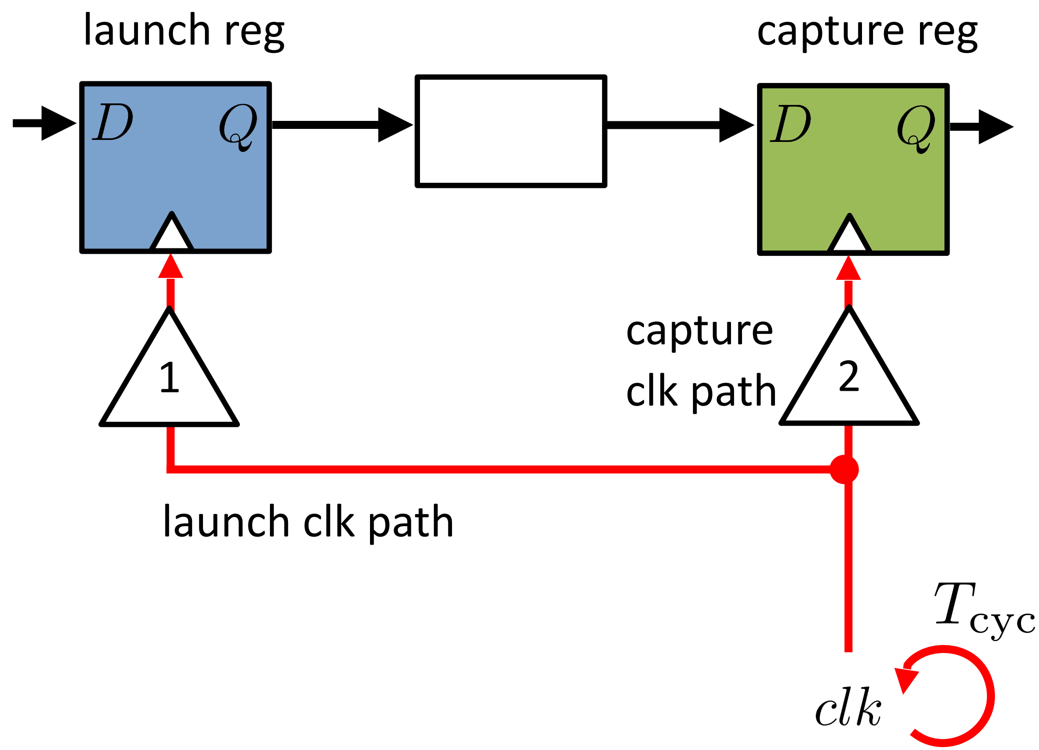
D
Q
clk
launch reg
capture reg
D
Q
D
Q
combinational path
1
2
capture
clk path
launch clk path
clk
3
4
5
6
1
2
0
D
stable t(A)
clk
Q
stable A

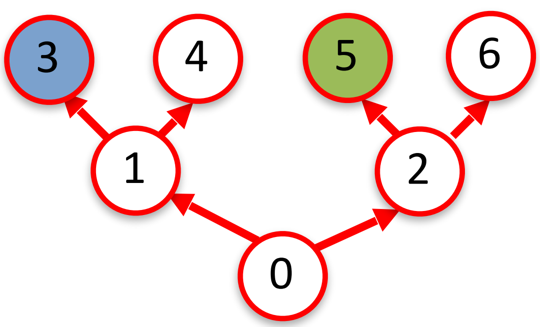


D
Q
clk
launch reg
capture reg
D
Q
D
Q
combinational path
1
capture
clk path
2
launch clk path
T_{cyc}
clk
D
stable t(A)
clk
Q
stable A
3
4
5
6
1
2
0

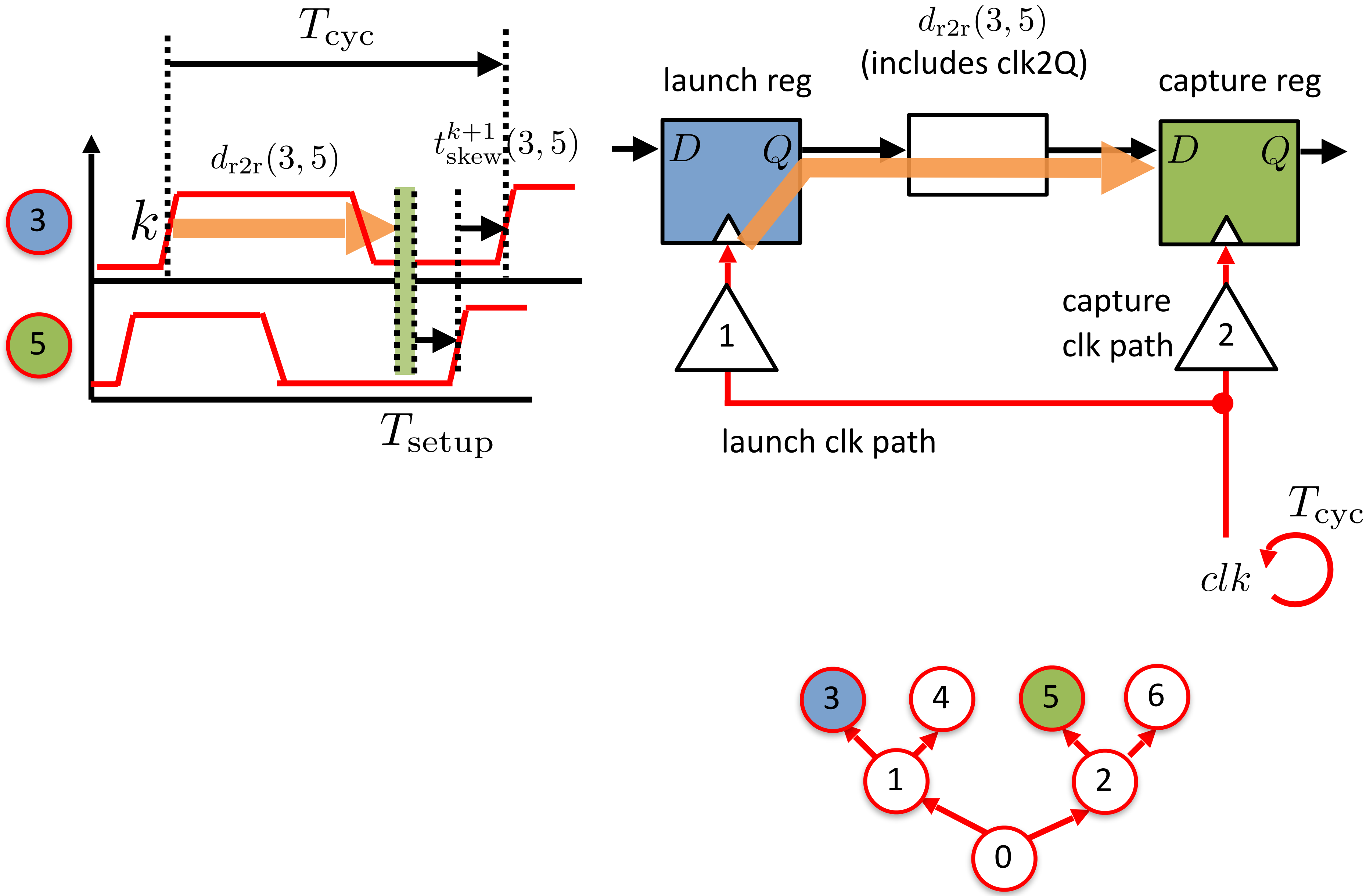

3
5
k
k
$t^k_{\text{skew}}(5,3)$
launch reg
capture reg
D
Q
D
Q
combinational path
capture
clk path
1
2
launch clk path
T_{cyc}
clk
3
4
5
6
1
2
0


0
5
k
k
$t^k_{\text{ins}}(5)$
launch reg
capture reg
D
Q
D
Q
combinational path
capture
clk path
1
2
launch clk path
T_{cyc}
clk
3
4
5
6
1
2
0

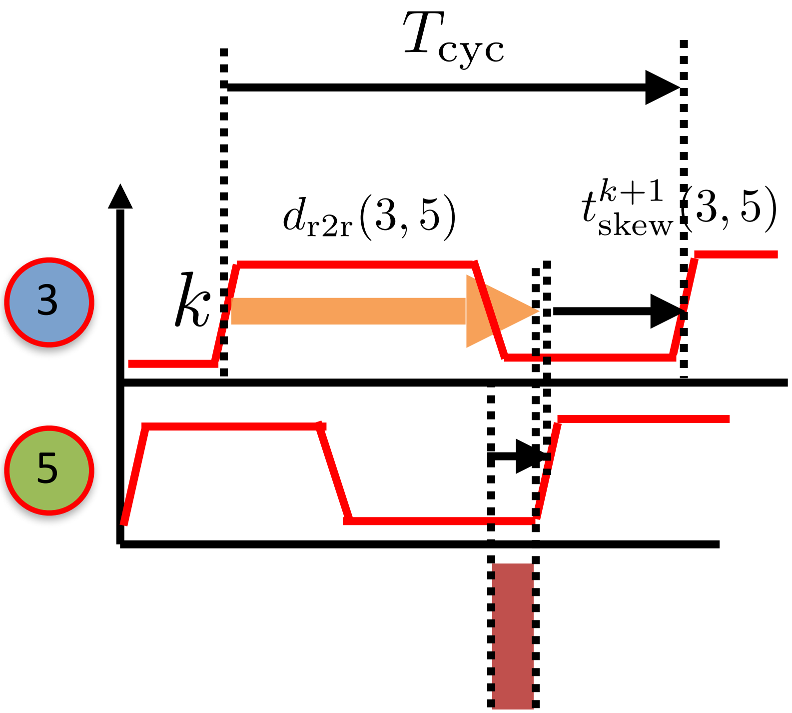

launch reg
D
Q
capture reg
D
Q
1
capture
clk path
2
launch clk path
T_{cyc}
clk

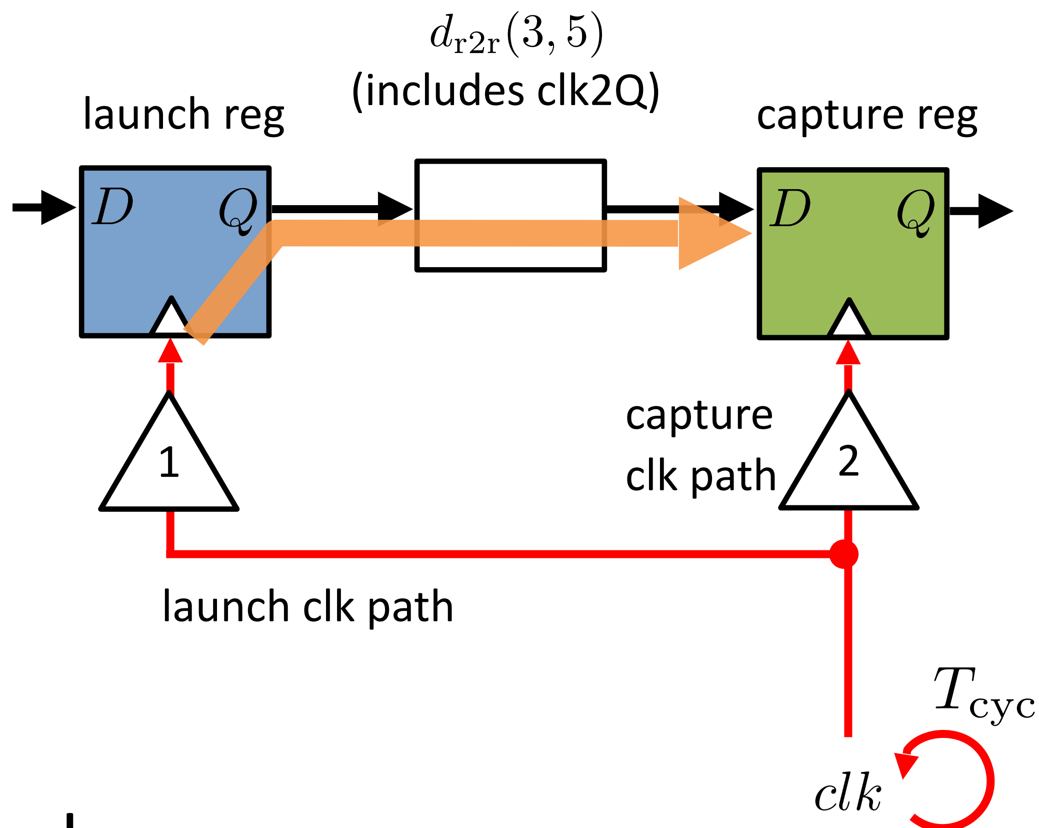

3
4
5
6
1
2
0

The setup constraint

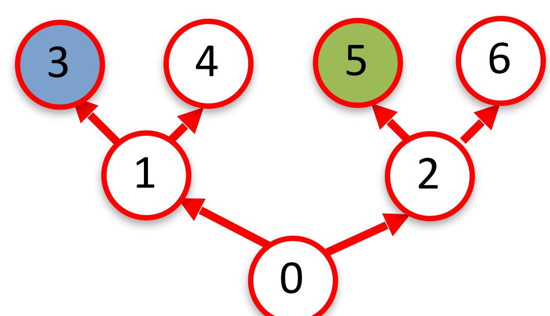


The setup constraint

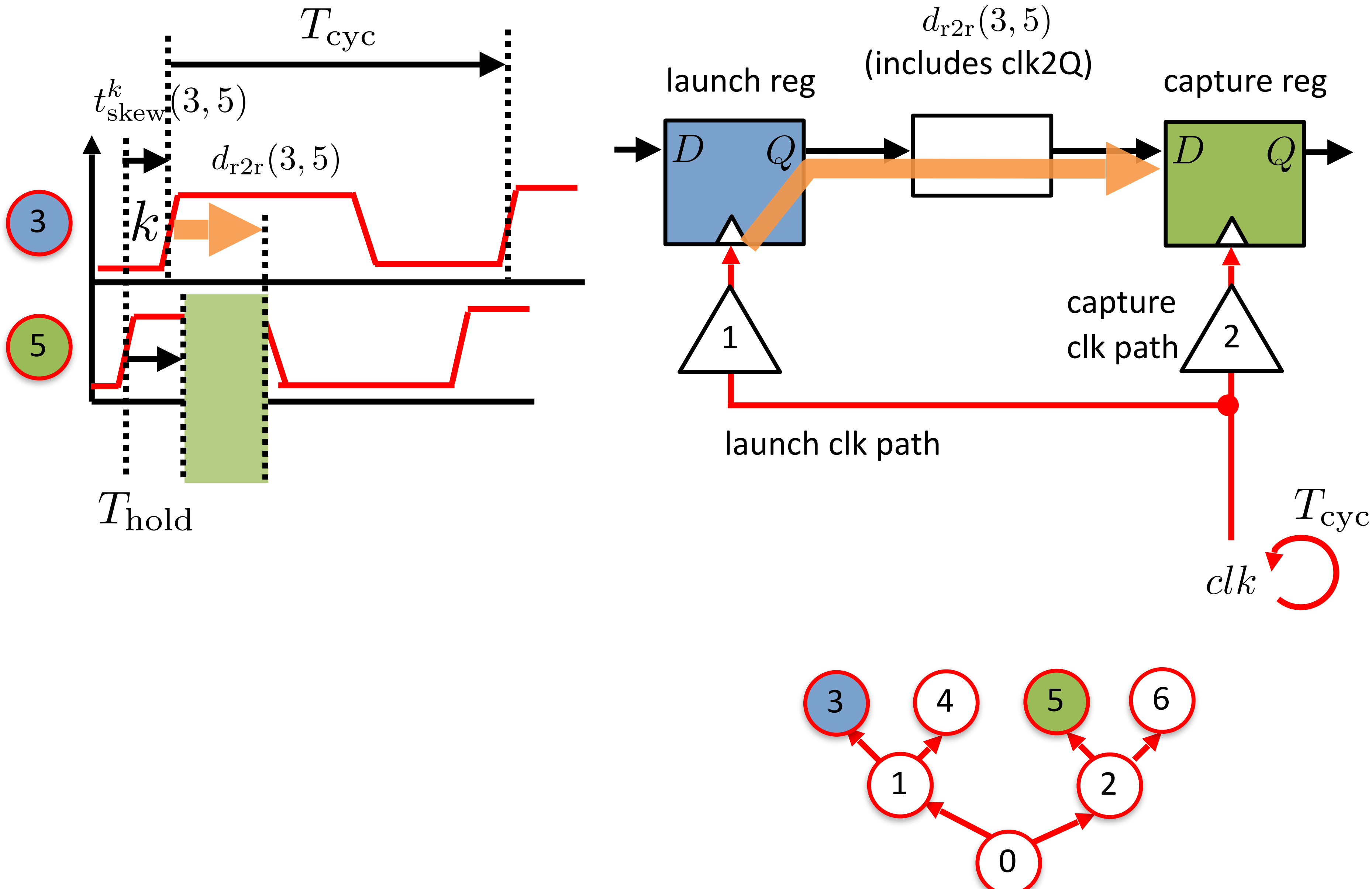




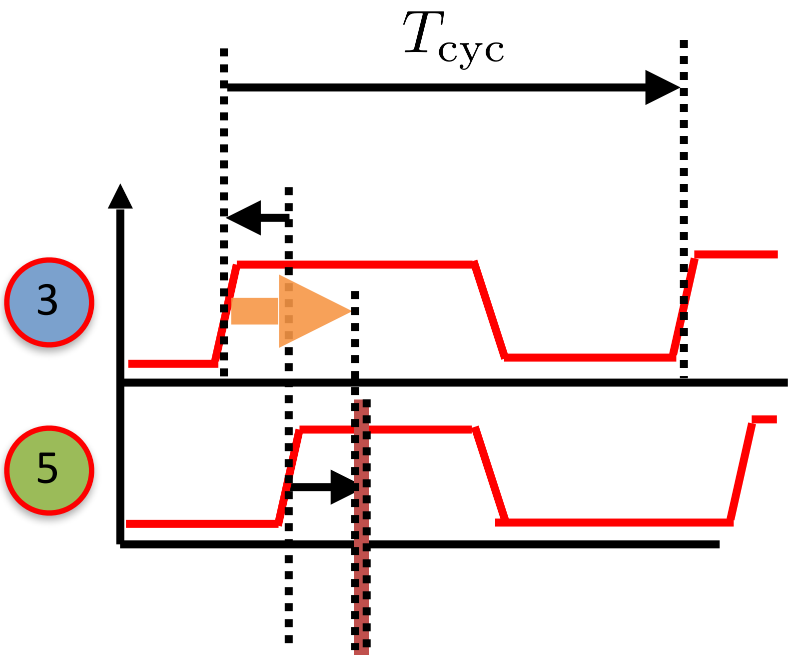
large pos. skew is bad

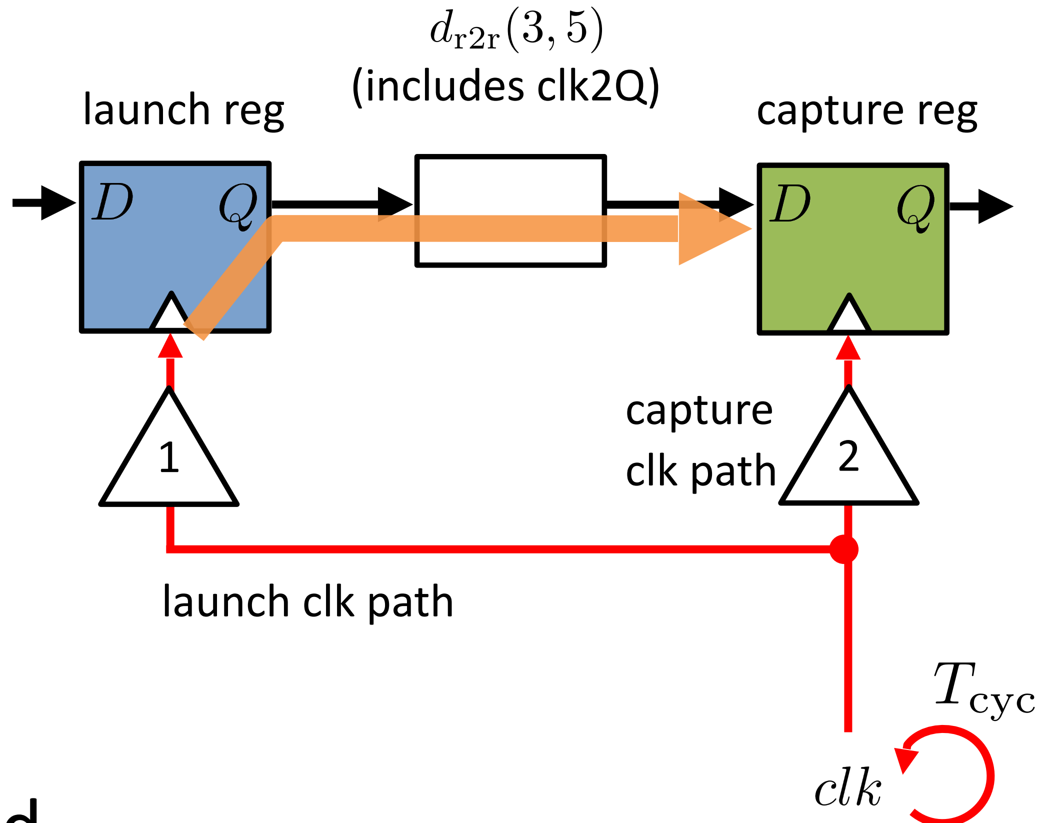


The hold constraint

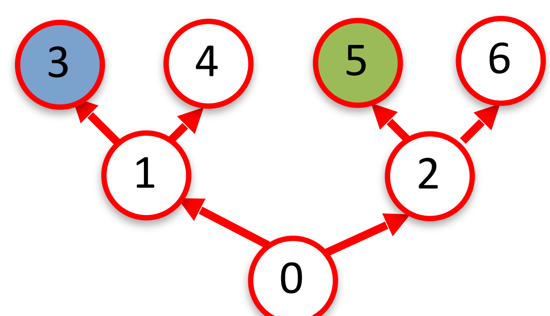


The hold constraint

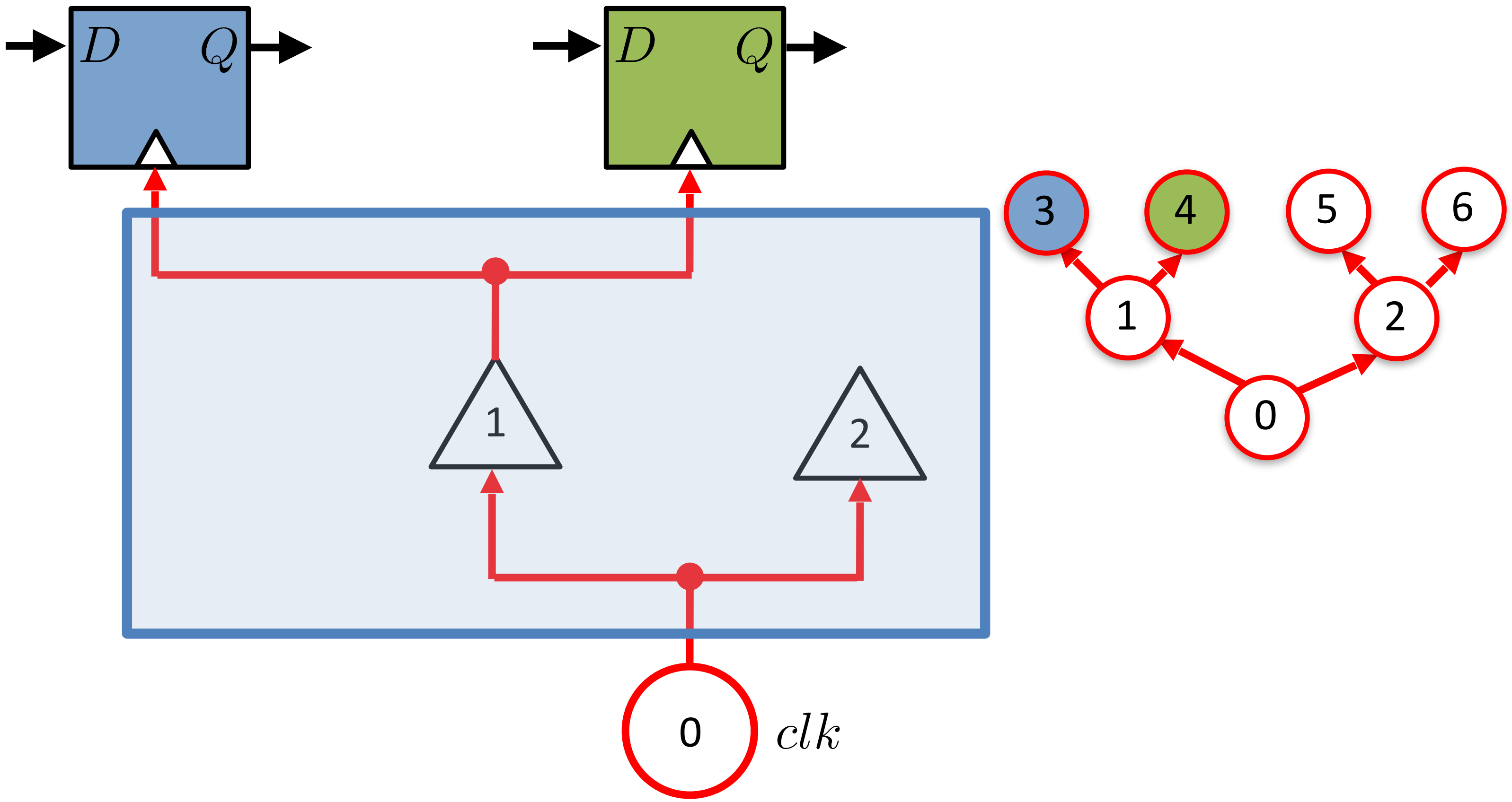




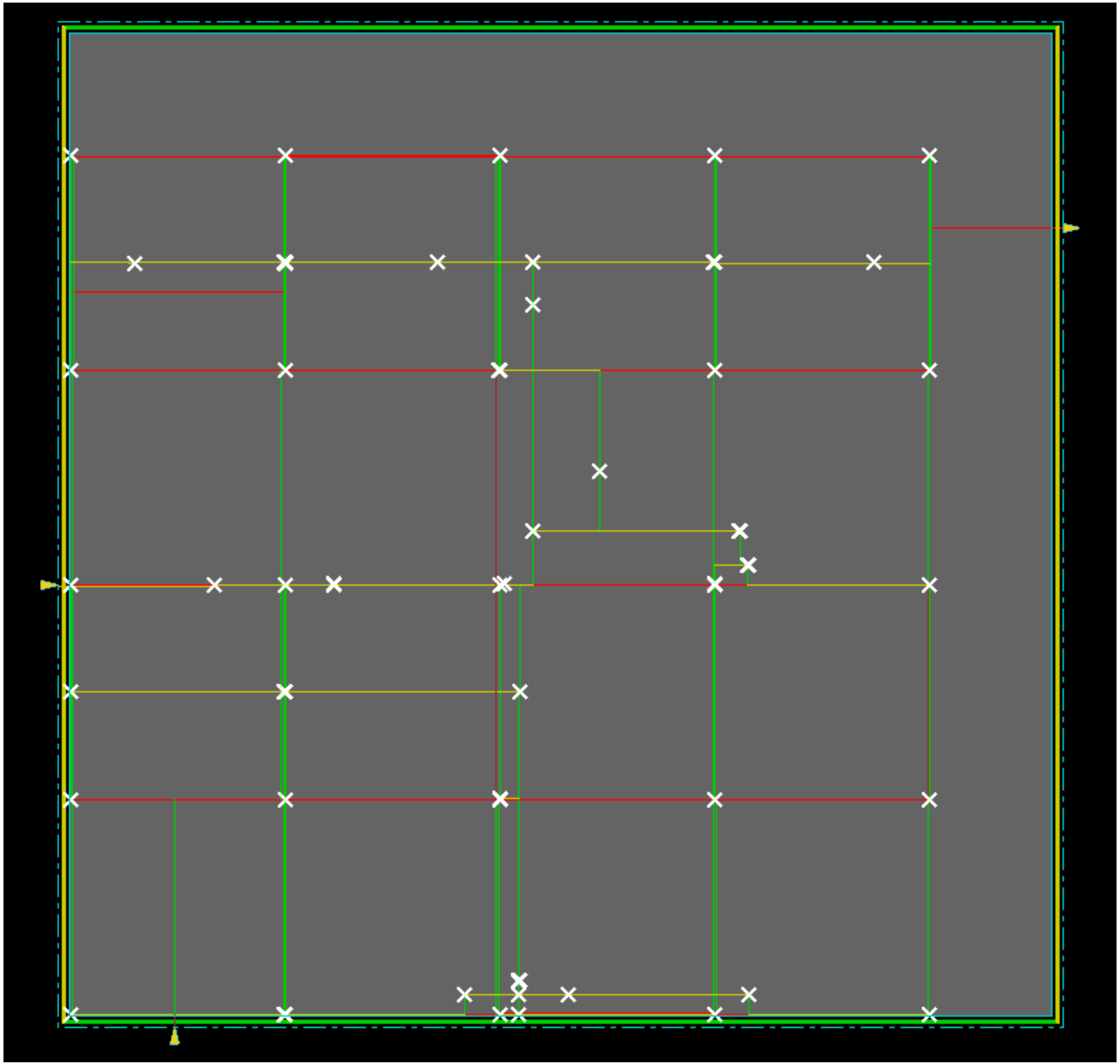
large neg. skew is bad



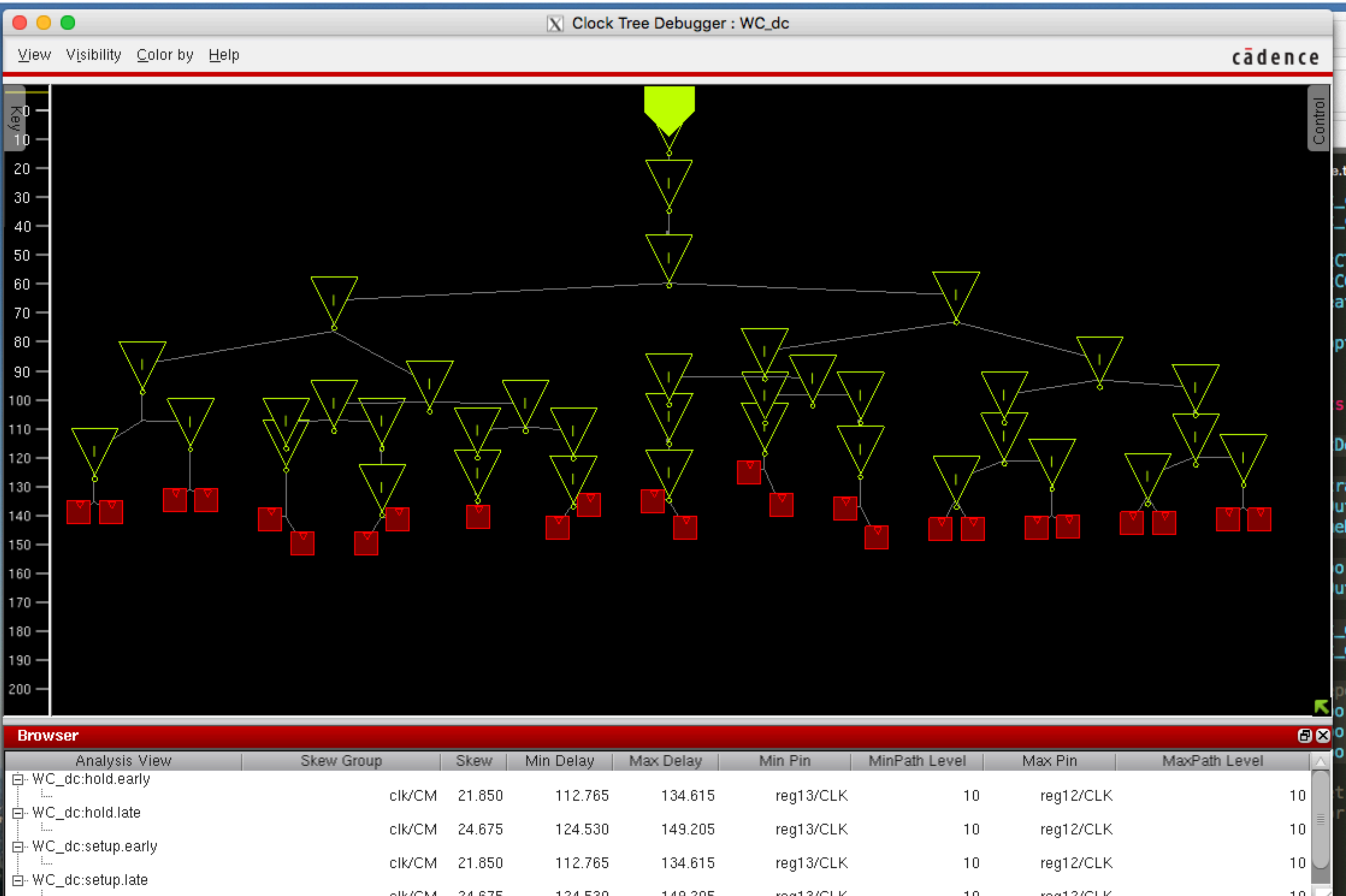
Clock distribution network



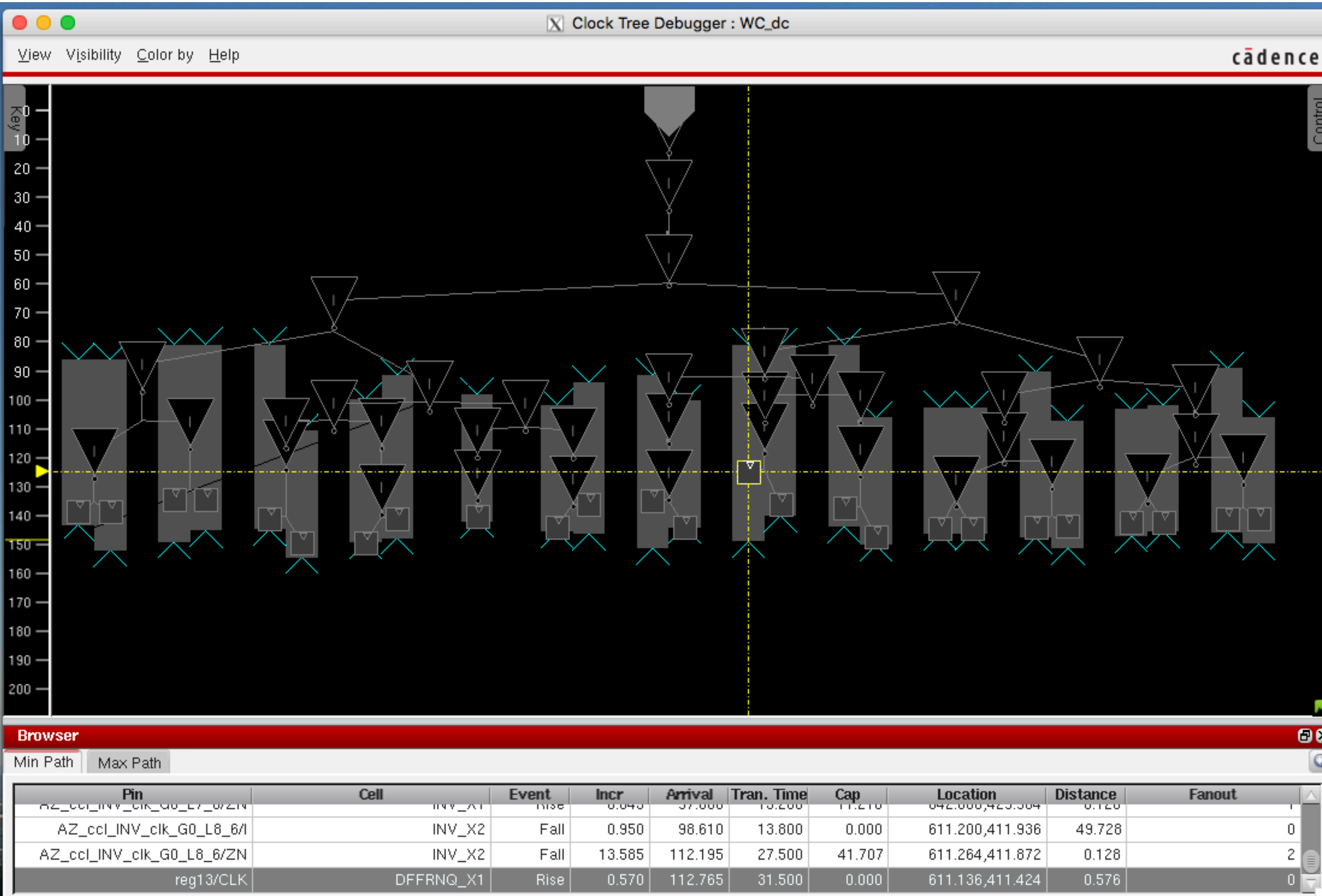
The clock



Its skew

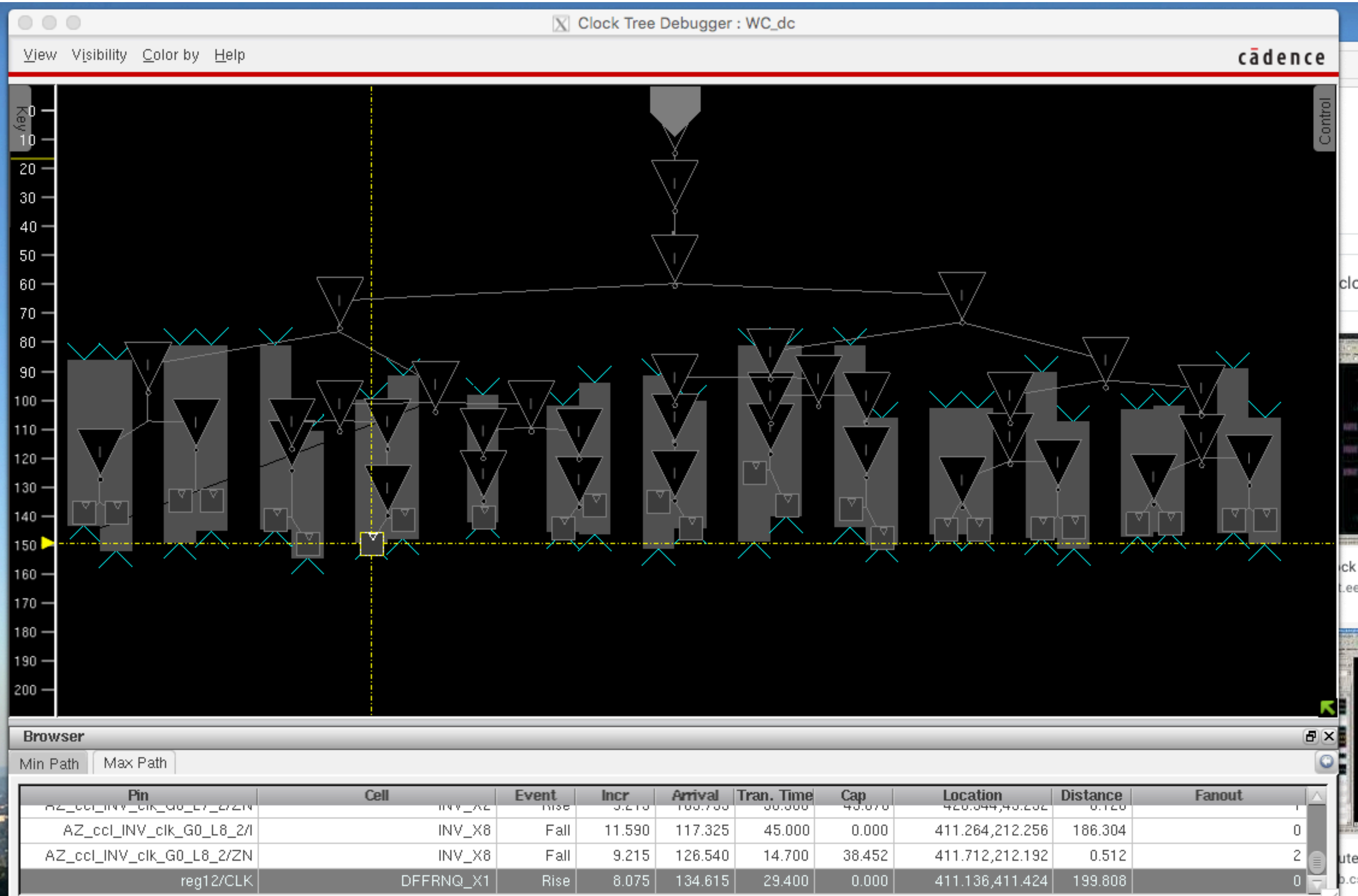

Clock Tree Debugger : WC_dc
View Visibility Color by Help
cadence
Key
Control
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Browser
Analysis View | Skew Group | Skew | Min Delay | Max Delay | Min Pin | MinPath Level | Max Pin | MaxPath Level
WC_dc:hold.early
clk/CM 21.850 112.765 134.615 reg13/CLK 10 reg12/CLK 10
WC_dc:hold.late
clk/CM 24.675 124.530 149.205 reg13/CLK 10 reg12/CLK 10
WC_dc:setup.early
clk/CM 21.850 112.765 134.615 reg13/CLK 10 reg12/CLK 10
WC_dc:setup.late

Minimum path

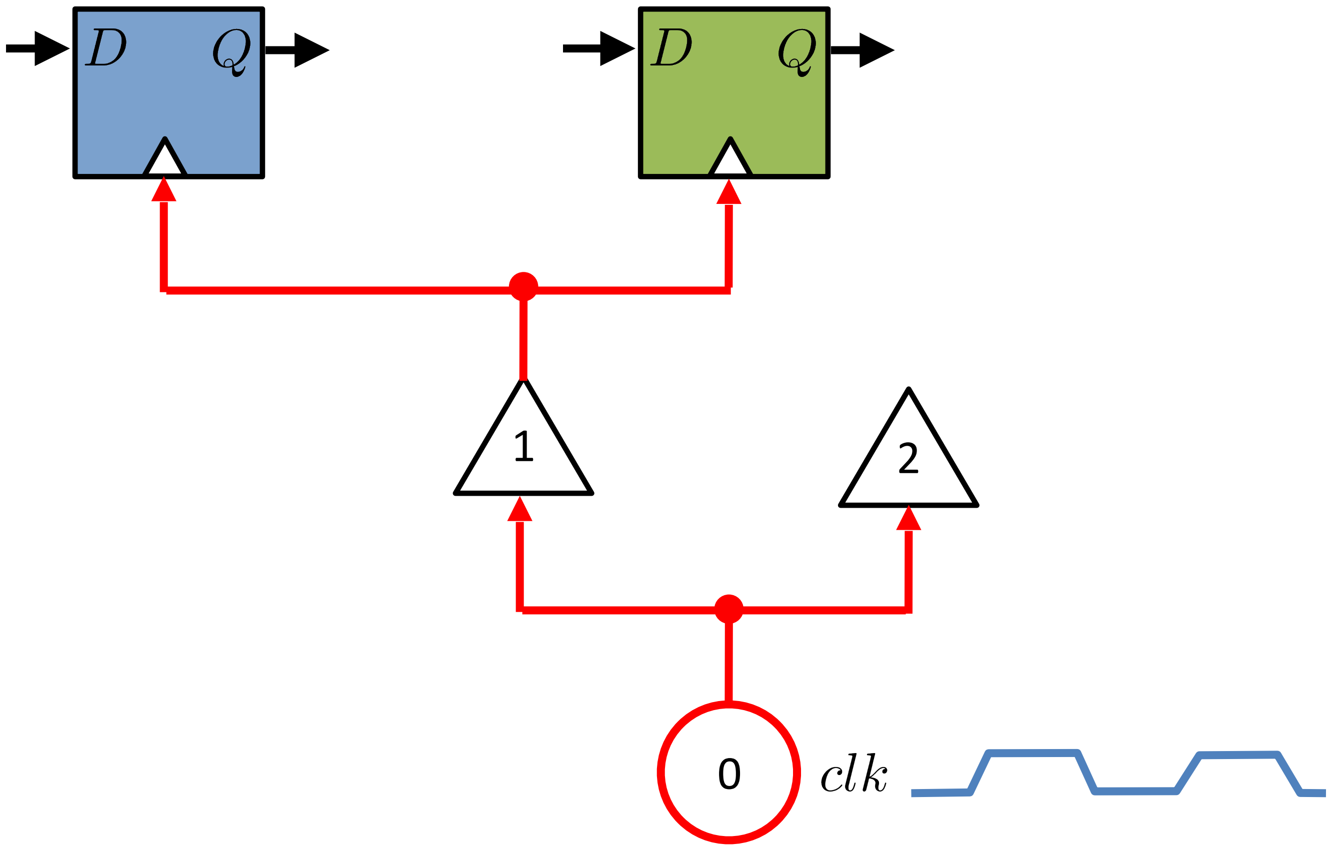


Pin	Cell	Event	Incr	Arrival	Tran. Time	Cap	Location	Distance	Fanout
AZ_ccl_INV_clk_G0_L8_6/I	INV_X2	Fall	0.950	98.610	13.800	0.000	611.200,411.936	49.728	0
AZ_ccl_INV_clk_G0_L8_6/ZN	INV_X2	Fall	13.585	112.195	27.500	41.707	611.264,411.872	0.128	2
reg13/CLK	DFFRNQ_X1	Rise	0.570	112.765	31.500	0.000	611.136,411.424	0.576	0

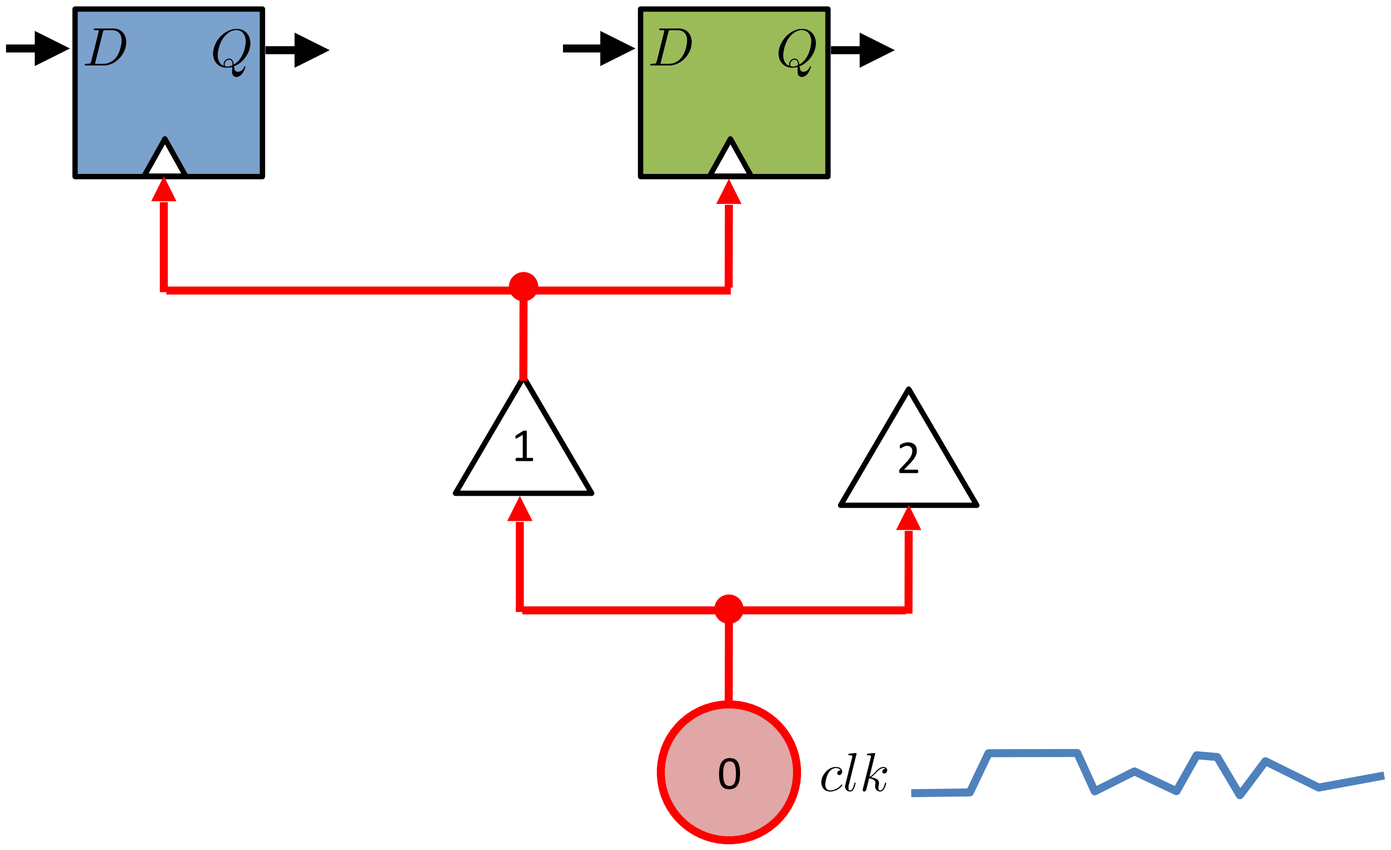
Maximum path



But …

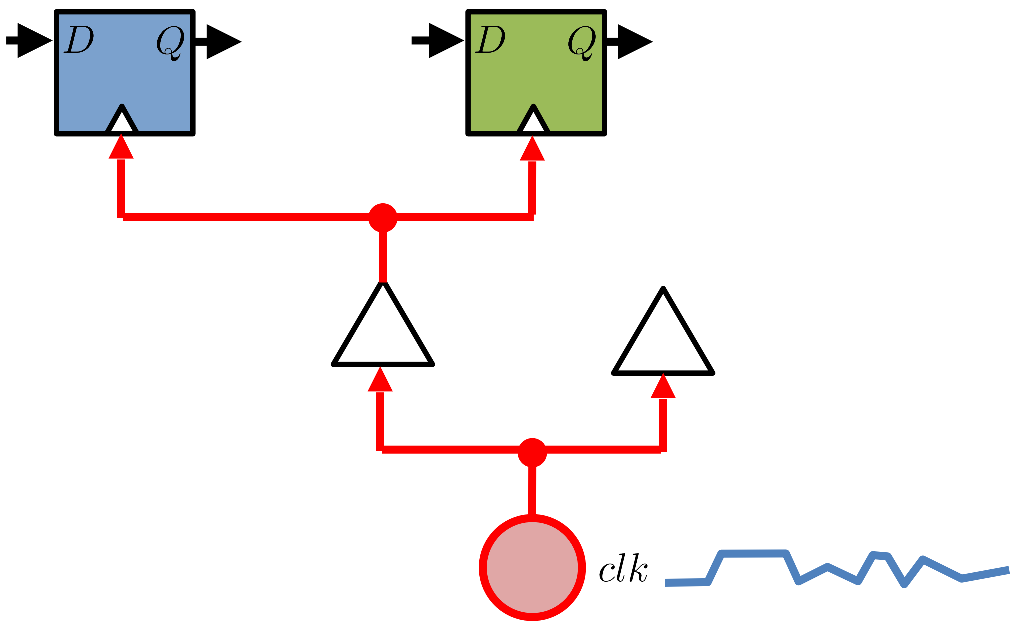


... faults

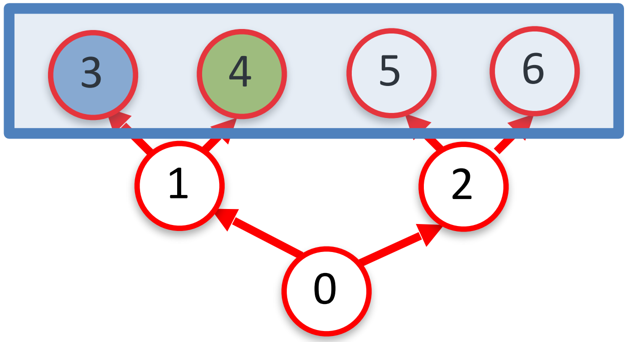


New requirements

Guarantee skew among some clock outputs despite faults



Pulse Synchronization



In pulse synchronization, *for each* $i \in \mathbb{N}$, *every (correct) node* $v \in V_g$ *generates* pulse *i exactly once*.

Let $p_{v,i}$ *denote the time when* v *generates the i-th pulse. We require that there are* $\mathcal{S}, P_{\max}, P_{\min} \in \mathbb{R}_{>0}$ *satisfying*

1. skew: $\sup_{i\in\mathbb{N},u,w\in V_g} \{|p_{v,i} - p_{w,i}|\} = \mathcal{S}$

2. per-1: $\inf_{i\in\mathbb{N}}\{\min_{v\in V_g} p_{v,i+1} - \max_{v\in V_g} p_{v,i}\} \geq P_{\min}$

3. per-2: $\sup_{i\in\mathbb{N}}\{\max_{v\in V_g} p_{v,i+1} - \min_{v\in V_g} p_{v,i}\} \leq P_{\max}$

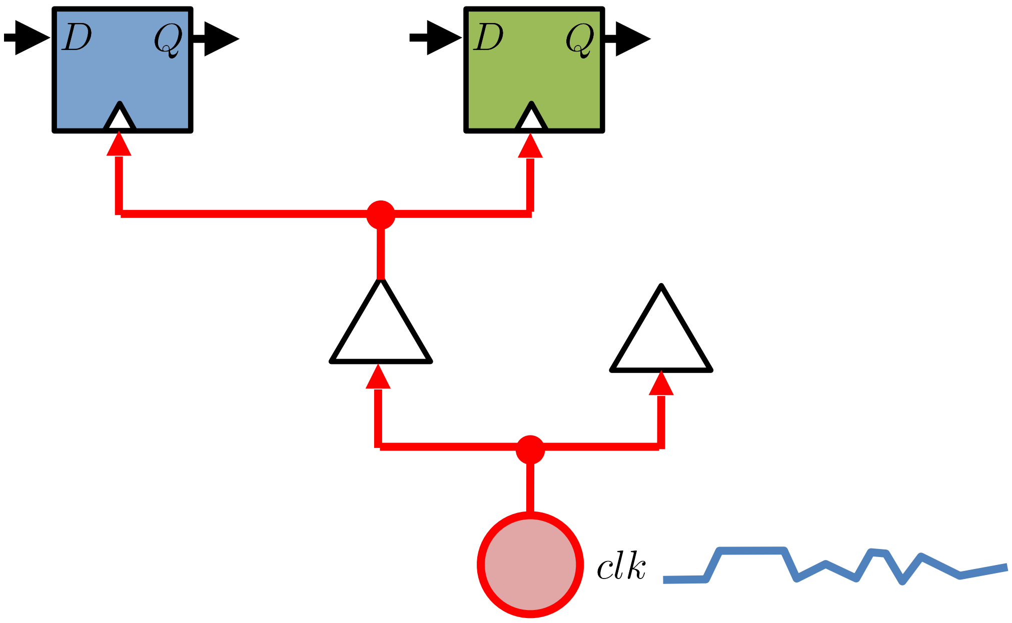
Lower bounds

Number of faults f. Then necessarily:

Global: $n > 3f$

Local: degree $> 2f$

Ideas?

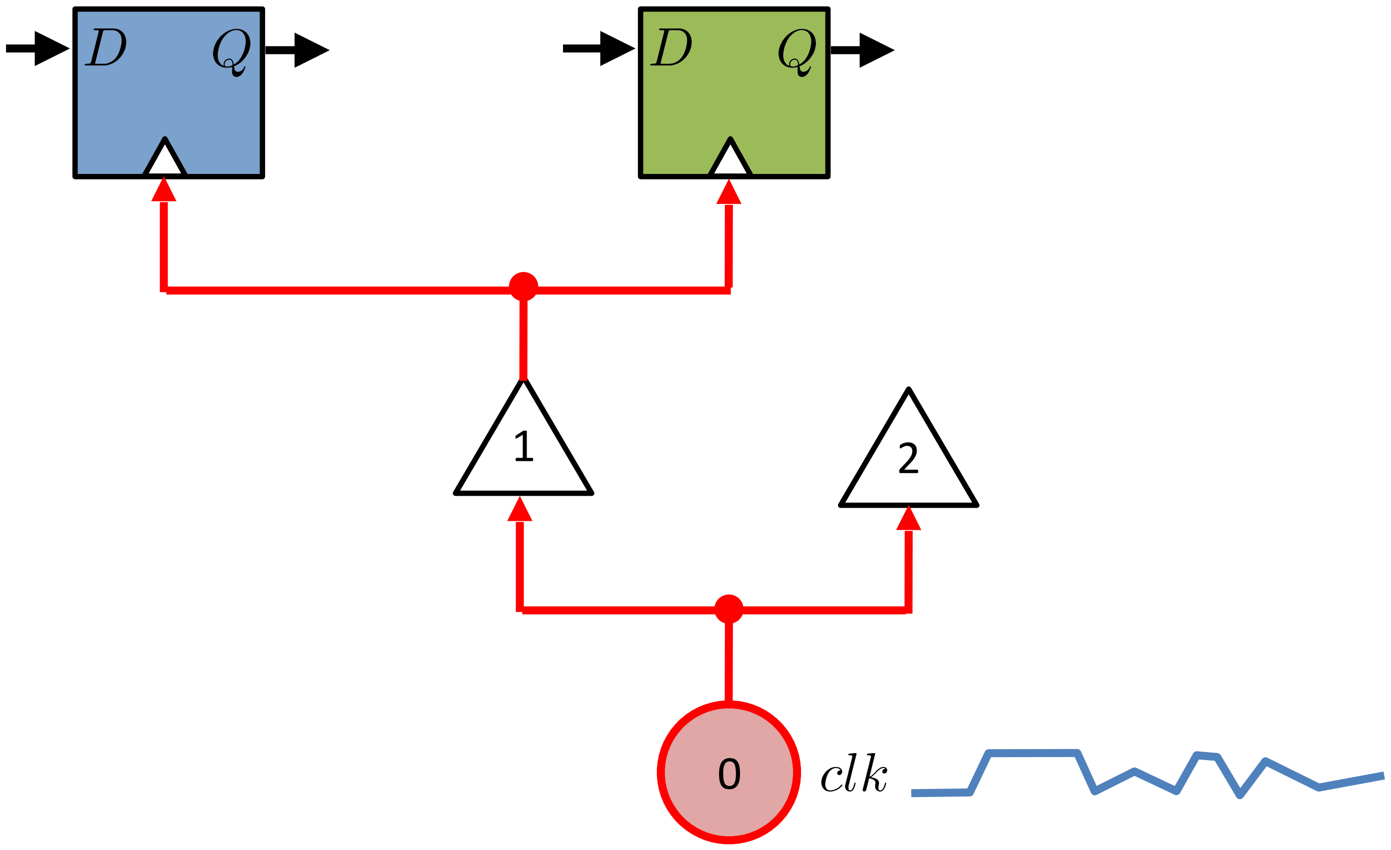


Chapter 11 (2)

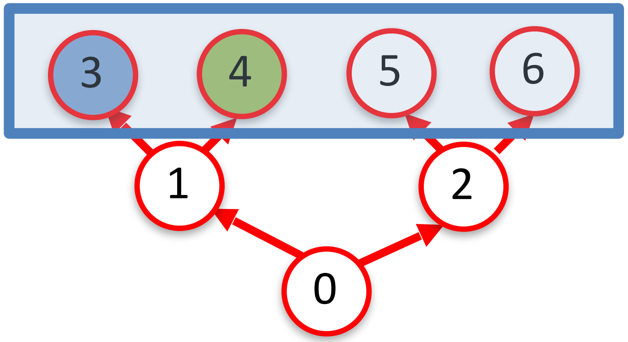
Low-degree clock distribution networks

Matthias Fuegger and Christoph Lenzen

Faults



Pulse Synchronization



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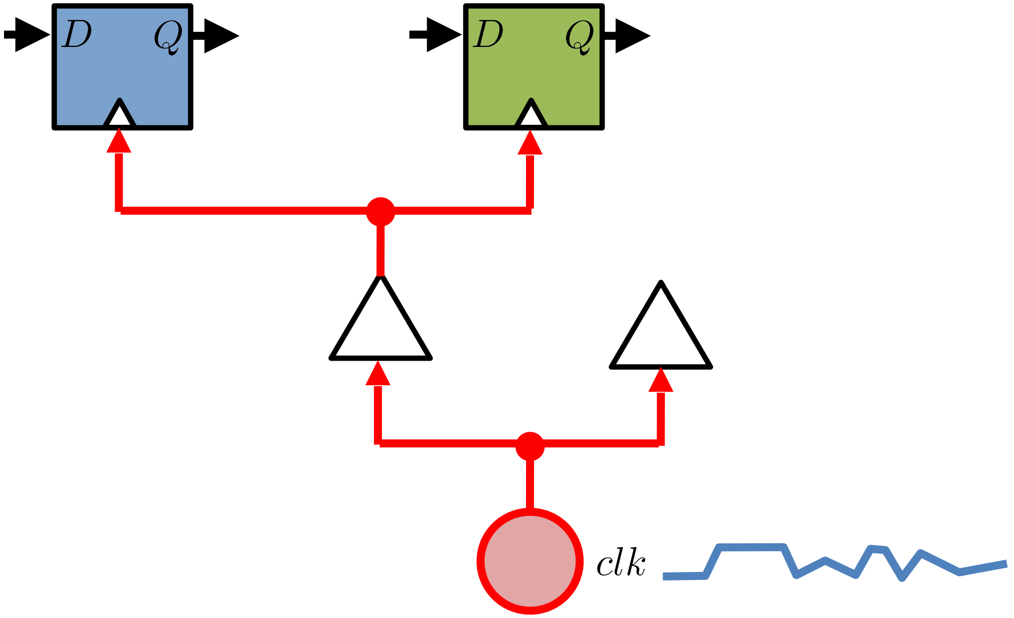
2. per-1: $\inf_{i \in \mathbb{N}} \{\min_{v \in V_g} p_{v,i+1} - \max_{v \in V_g} p_{v,i}\} \geq P_{\min}$

3. per-2: $\sup_{i \in \mathbb{N}} \{\max_{v \in V_g} p_{v,i+1} - \min_{v \in V_g} p_{v,i}\} \leq P_{\max}$

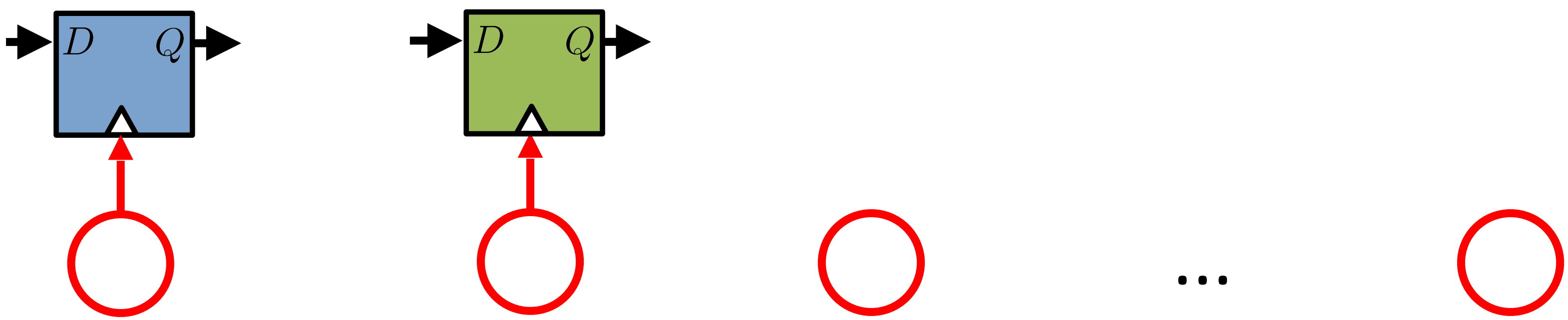
Last time: ideas session



Idea 1: only LW algorithm

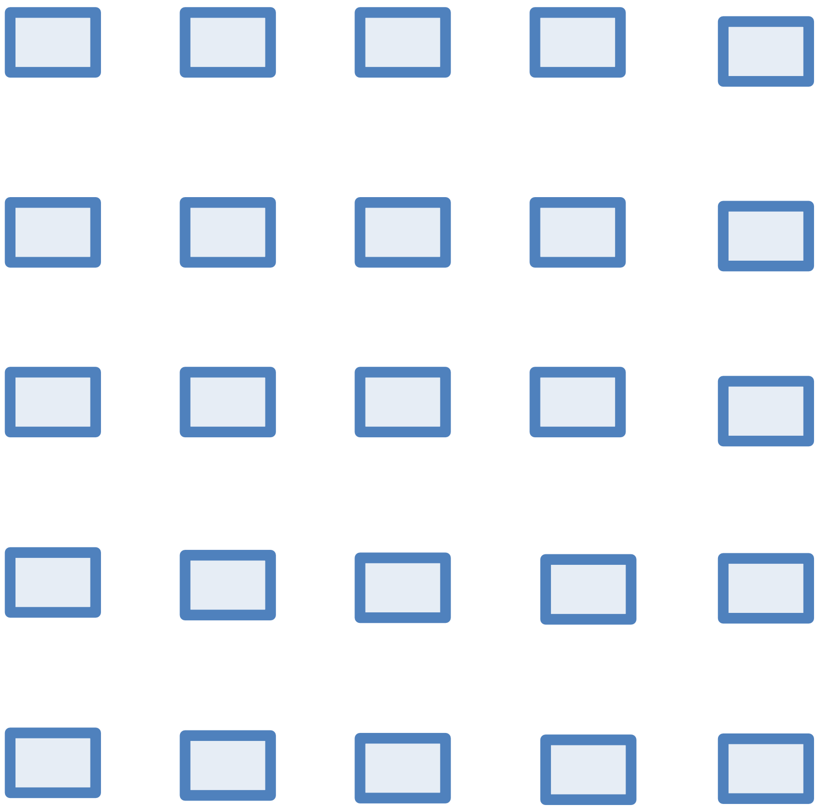
no tree, only LW

3f+1



Idea 1

5x5 grid

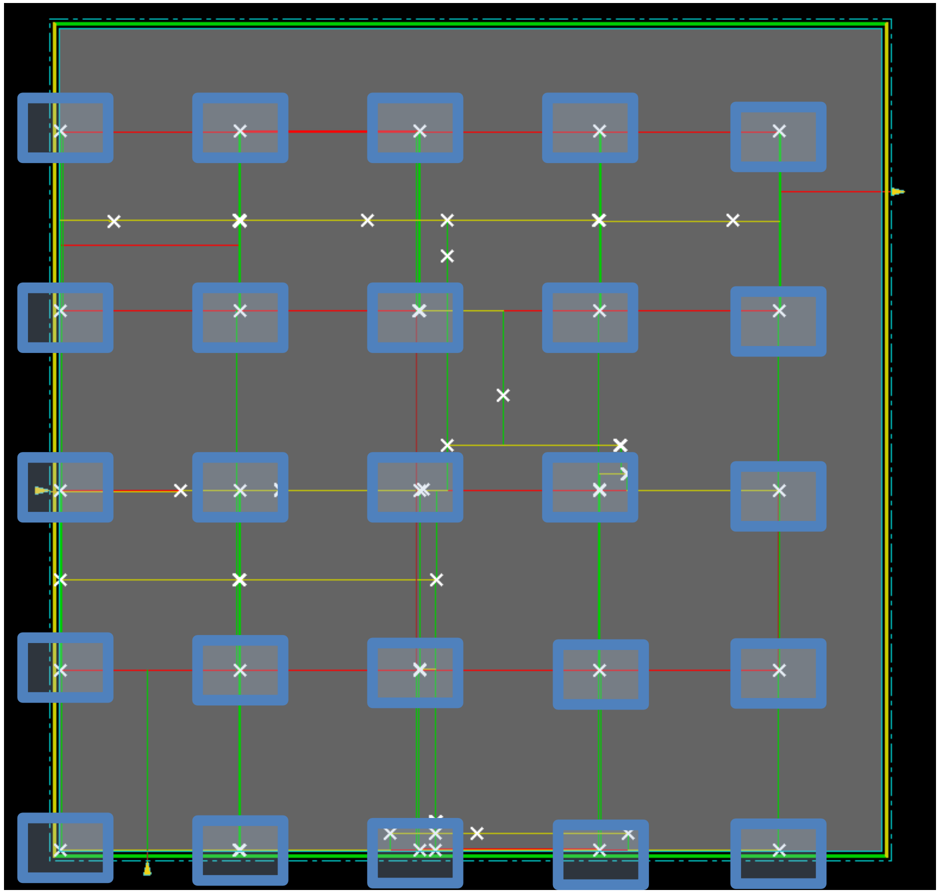


properties:

- **fault tolerance?**
- cost?
- skew?

Idea 1

5x5 grid

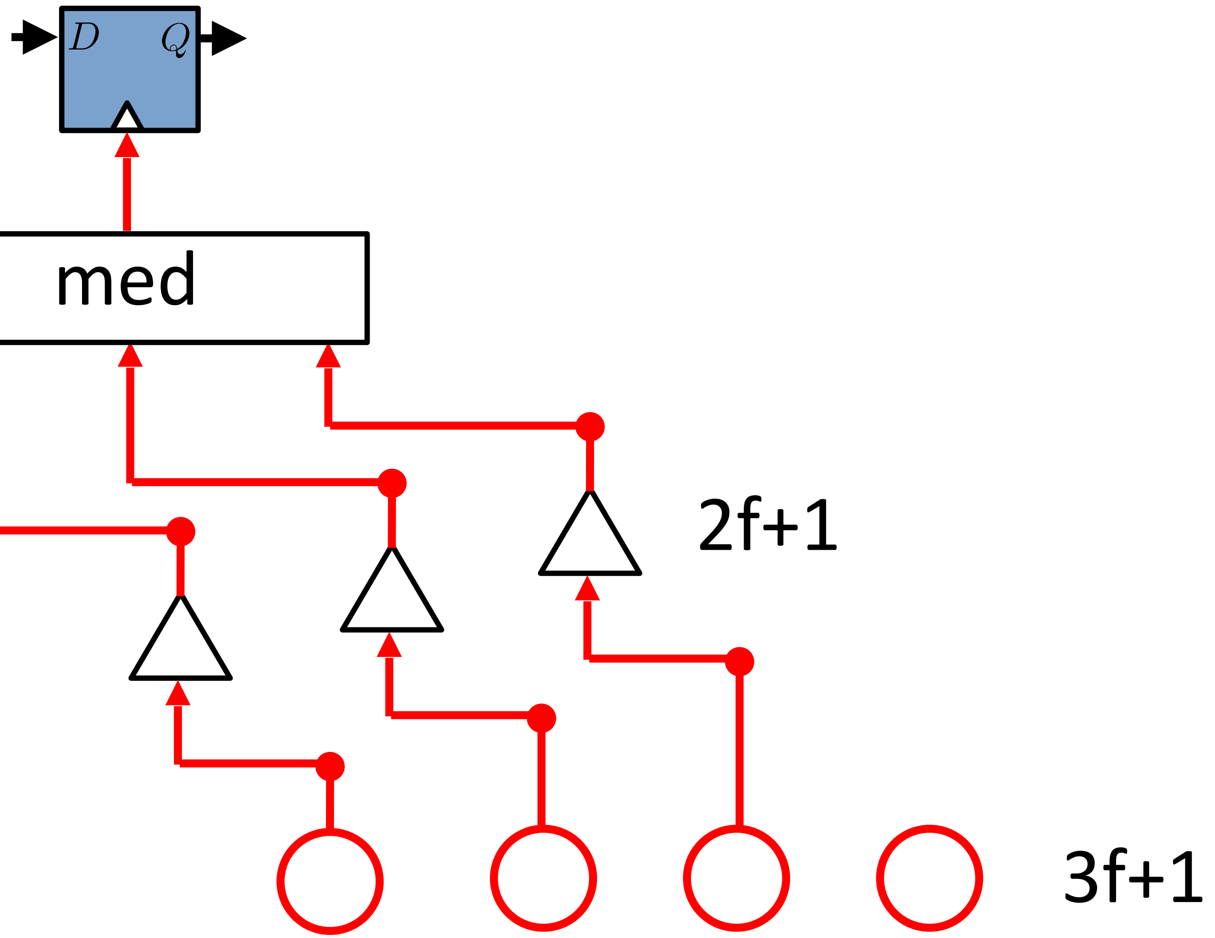


properties:

- fault tolerance?
- cost?
- skew?

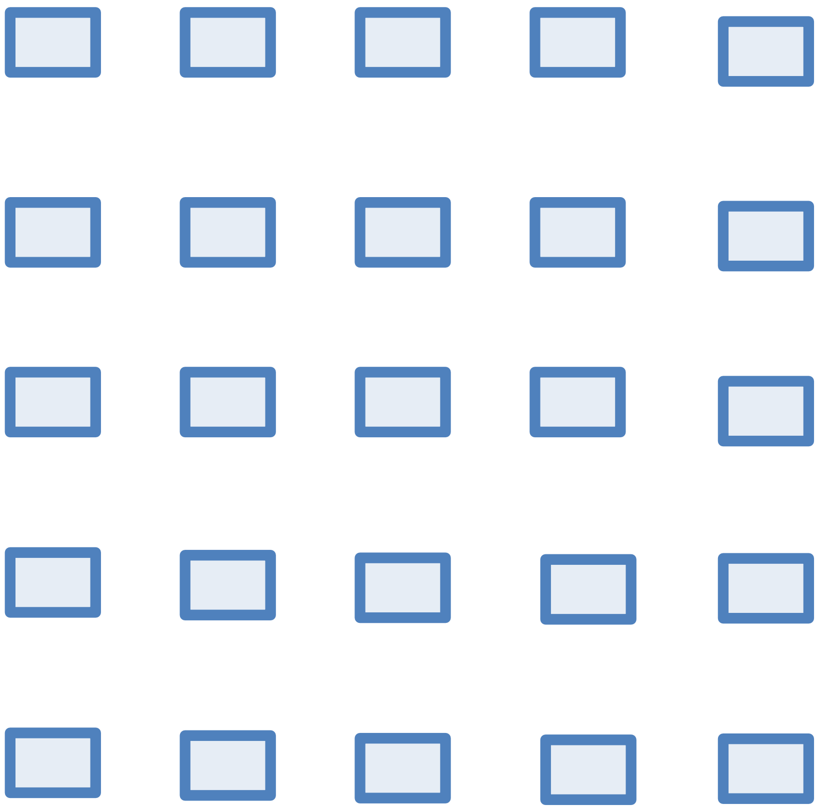
Idea 2: redundant trees

replicate the clock source, vote on output



Idea 2

5x5 grid

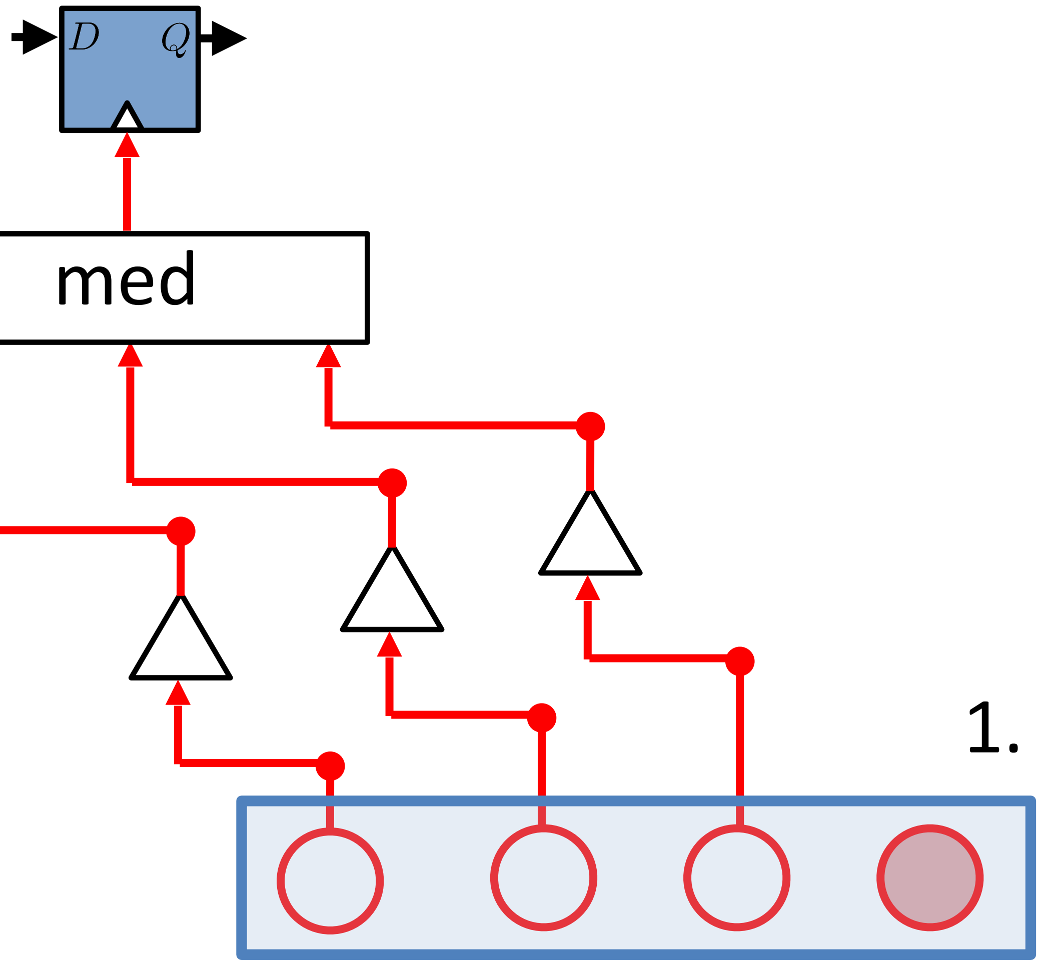


properties:

- fault tolerance?
- skew?
- cost?

Fault tolerance

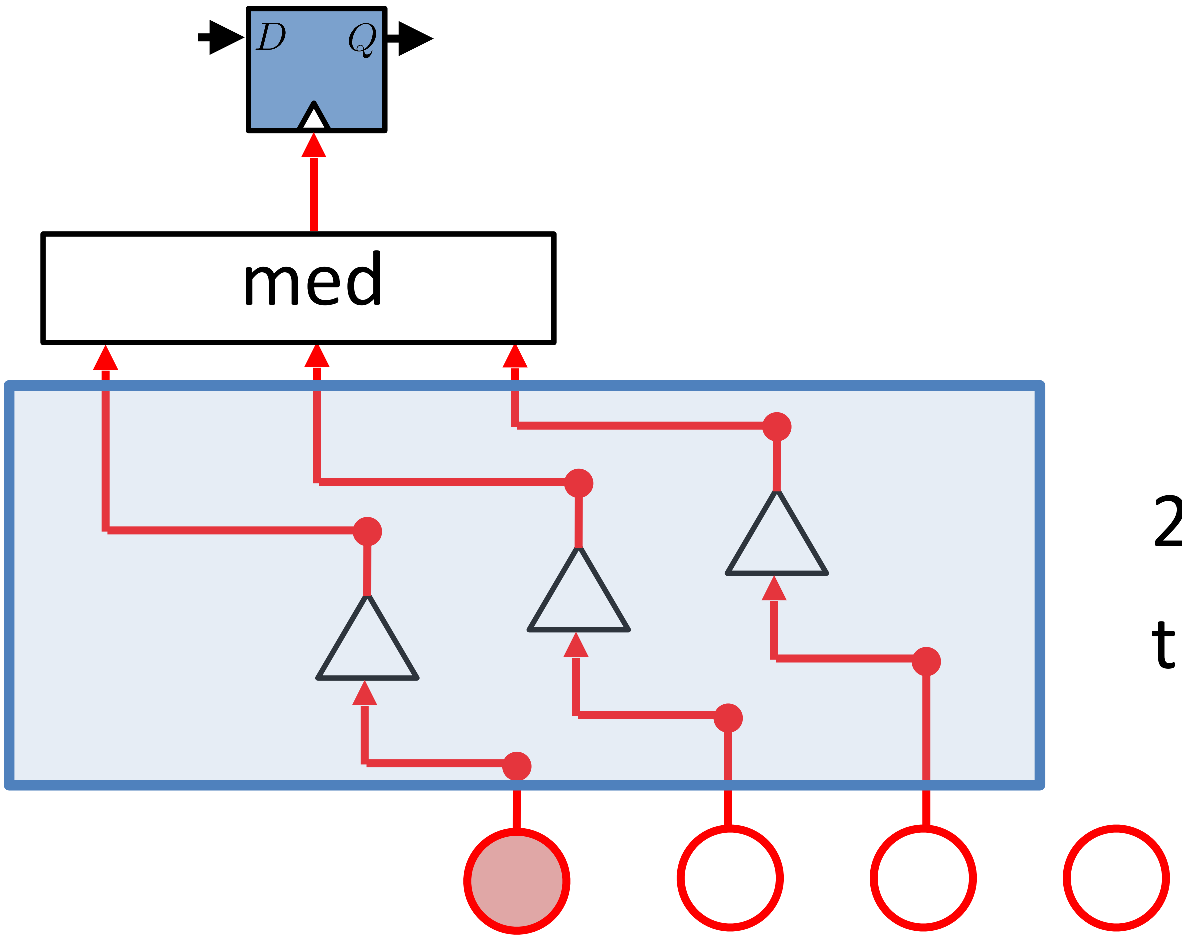
replicate the clock source, vote on output



1. at most f fail

Fault tolerance

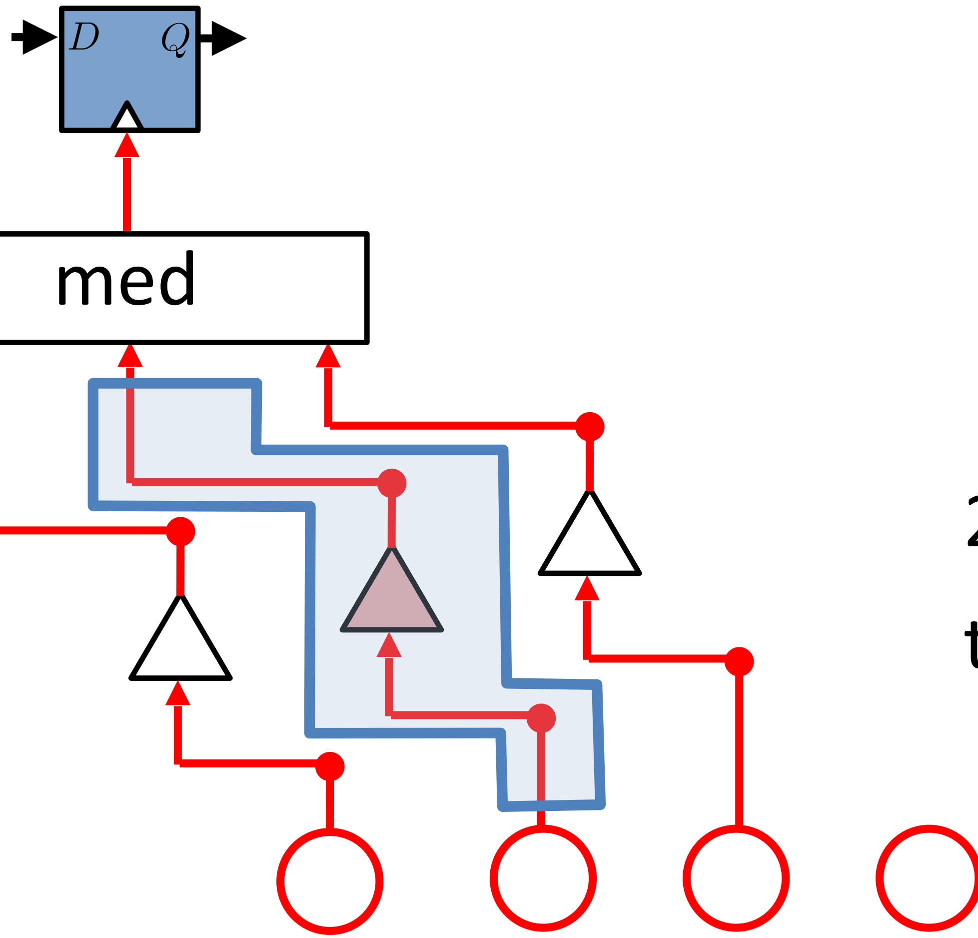
replicate the clock source, vote on output



2. at most f trees fail

Fault tolerance

replicate the clock source, vote on output

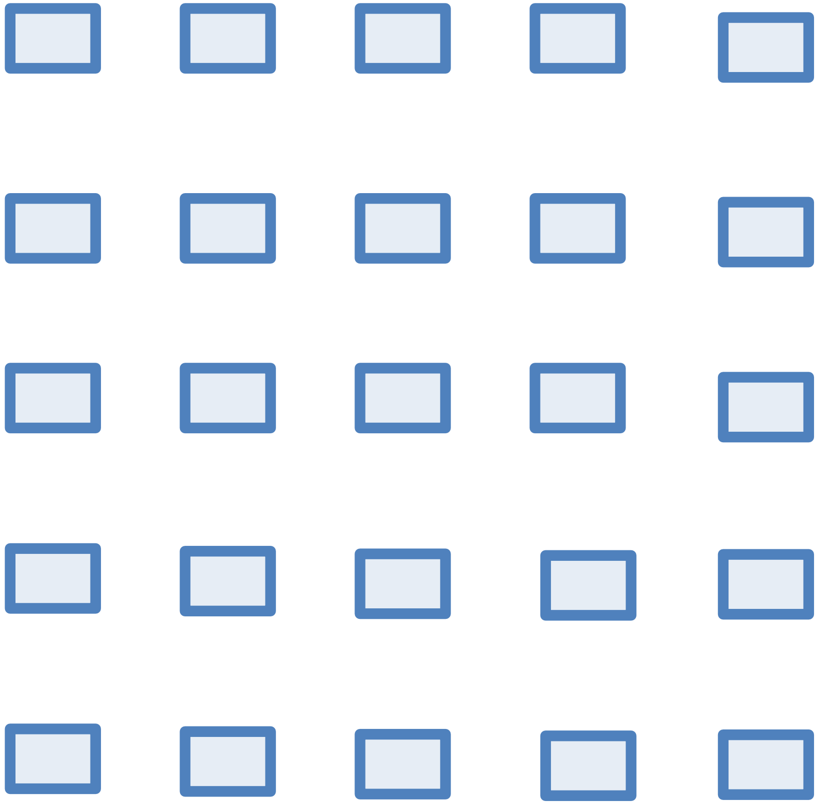


2. at most f

trees fail

Idea 2

5x5 grid



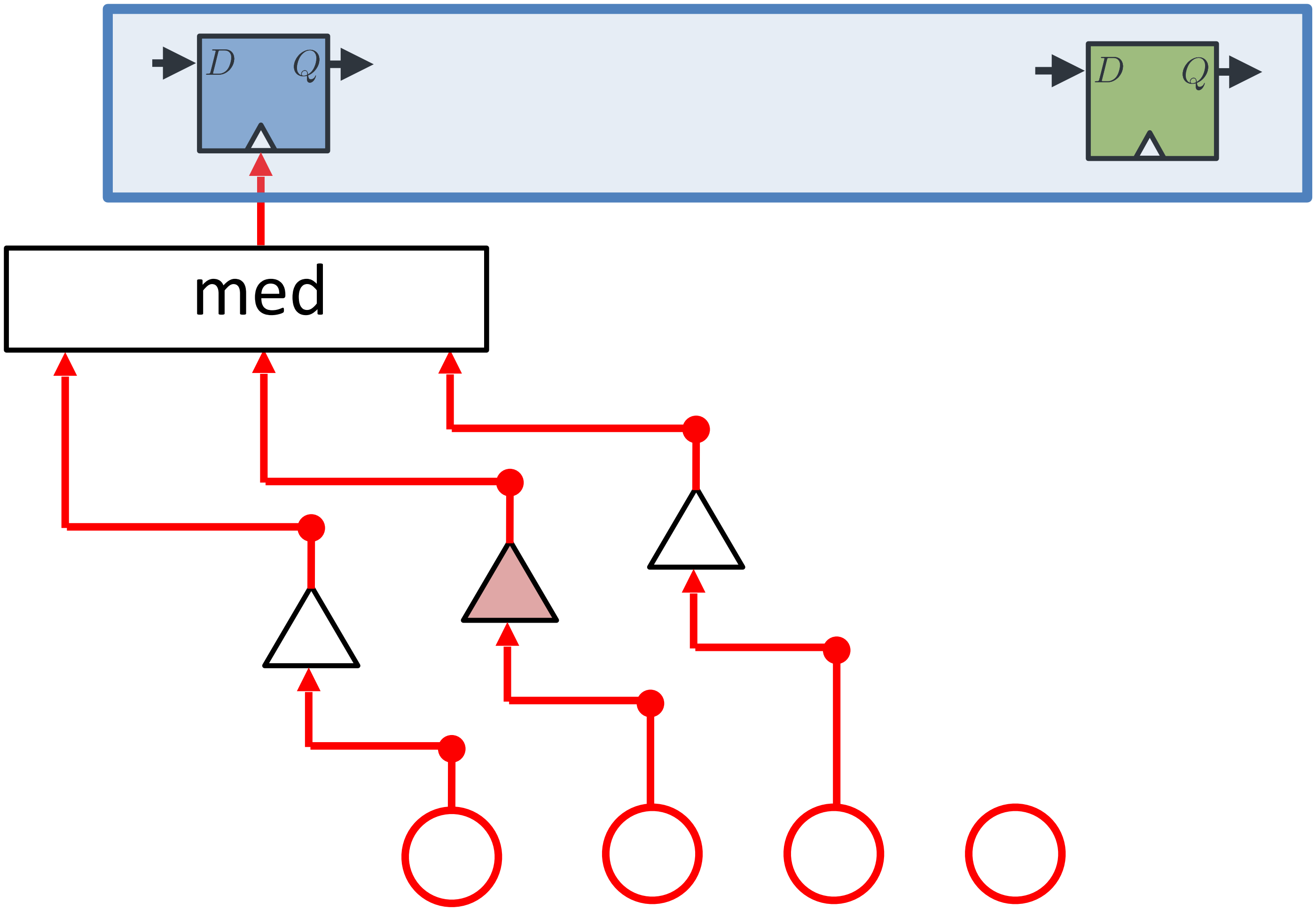
properties:

- fault tolerance?

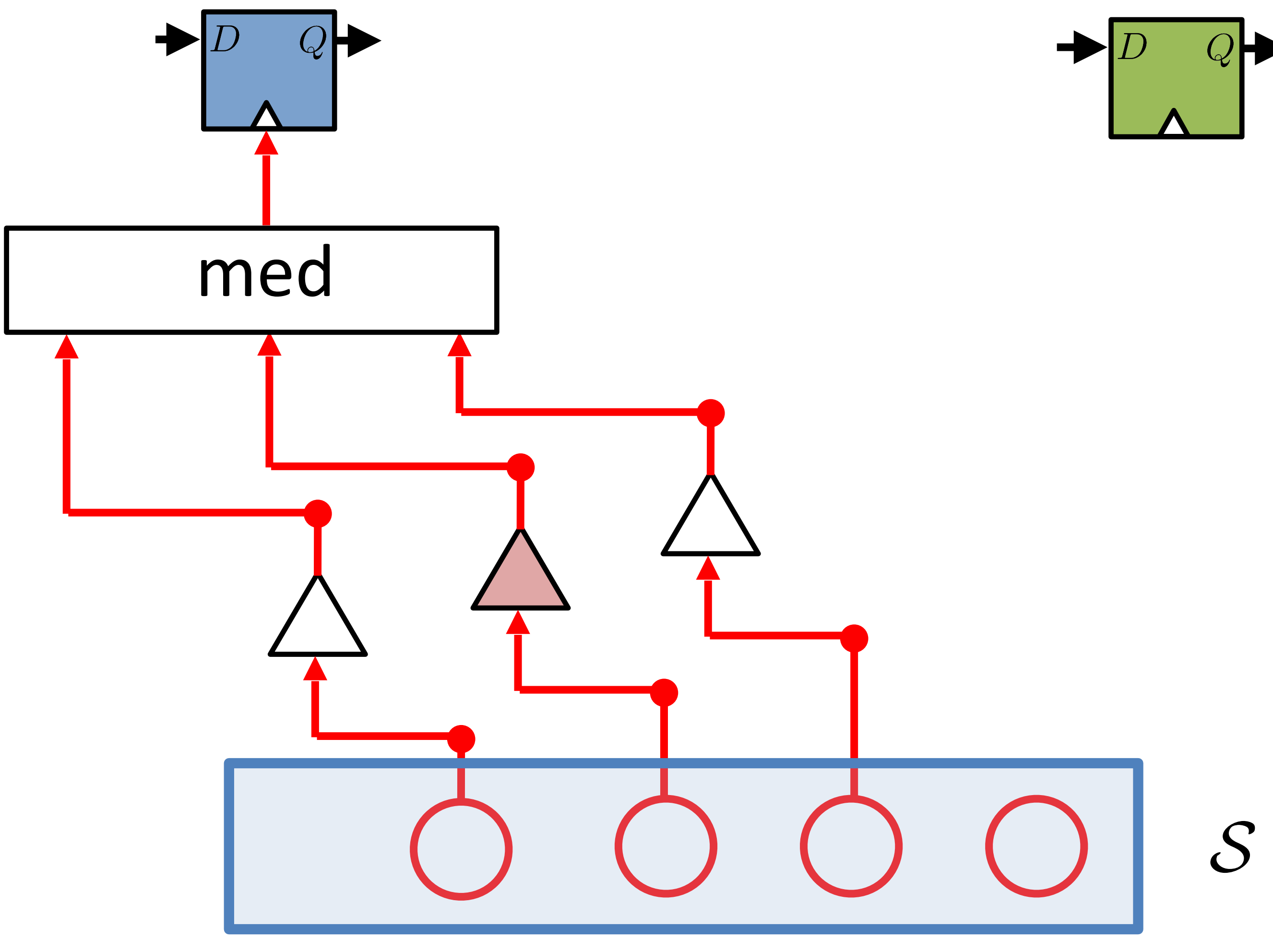
- **skew?**

- cost?

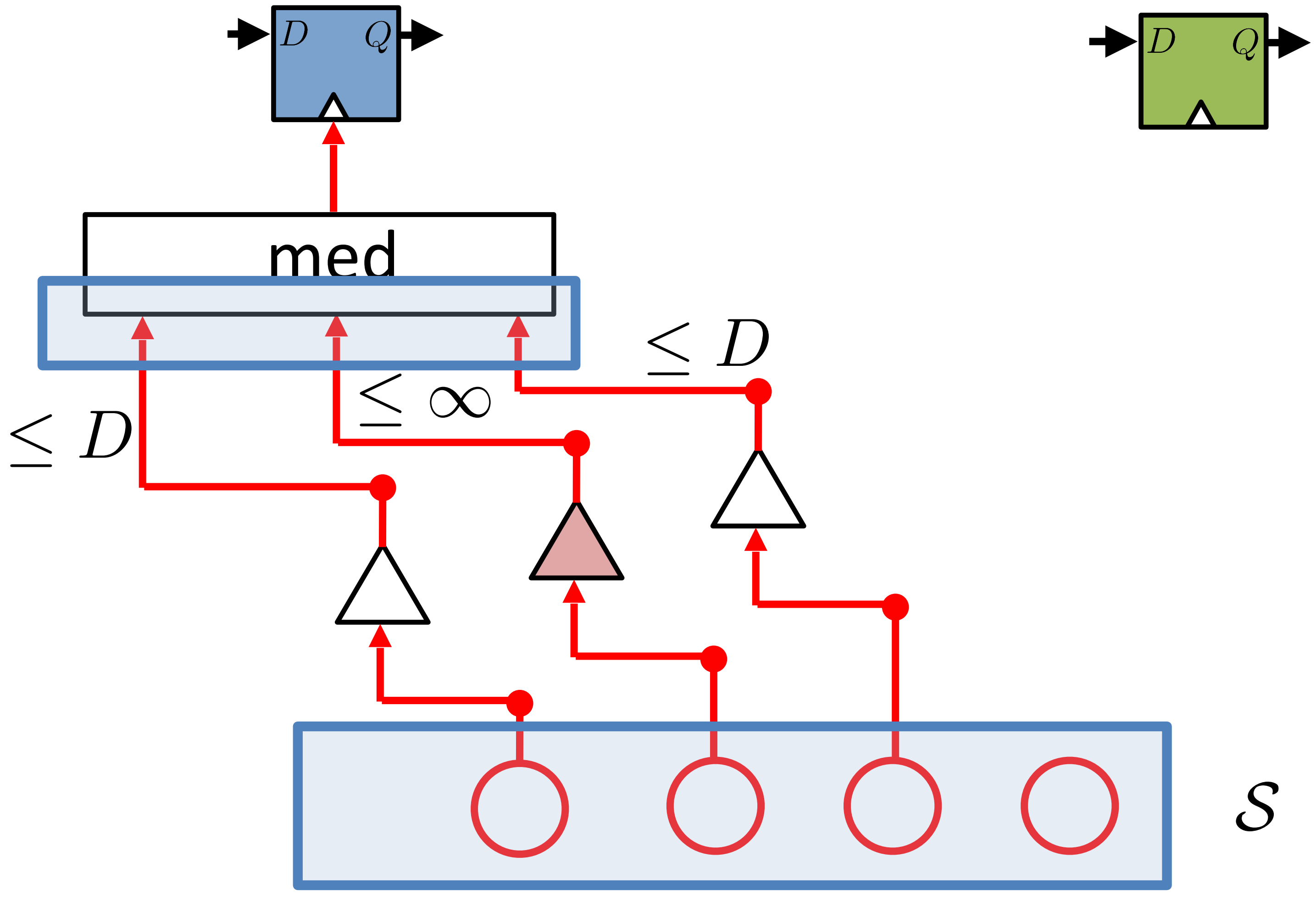
Skew



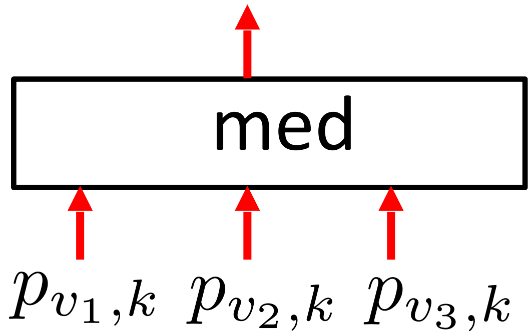
Skew



Skew

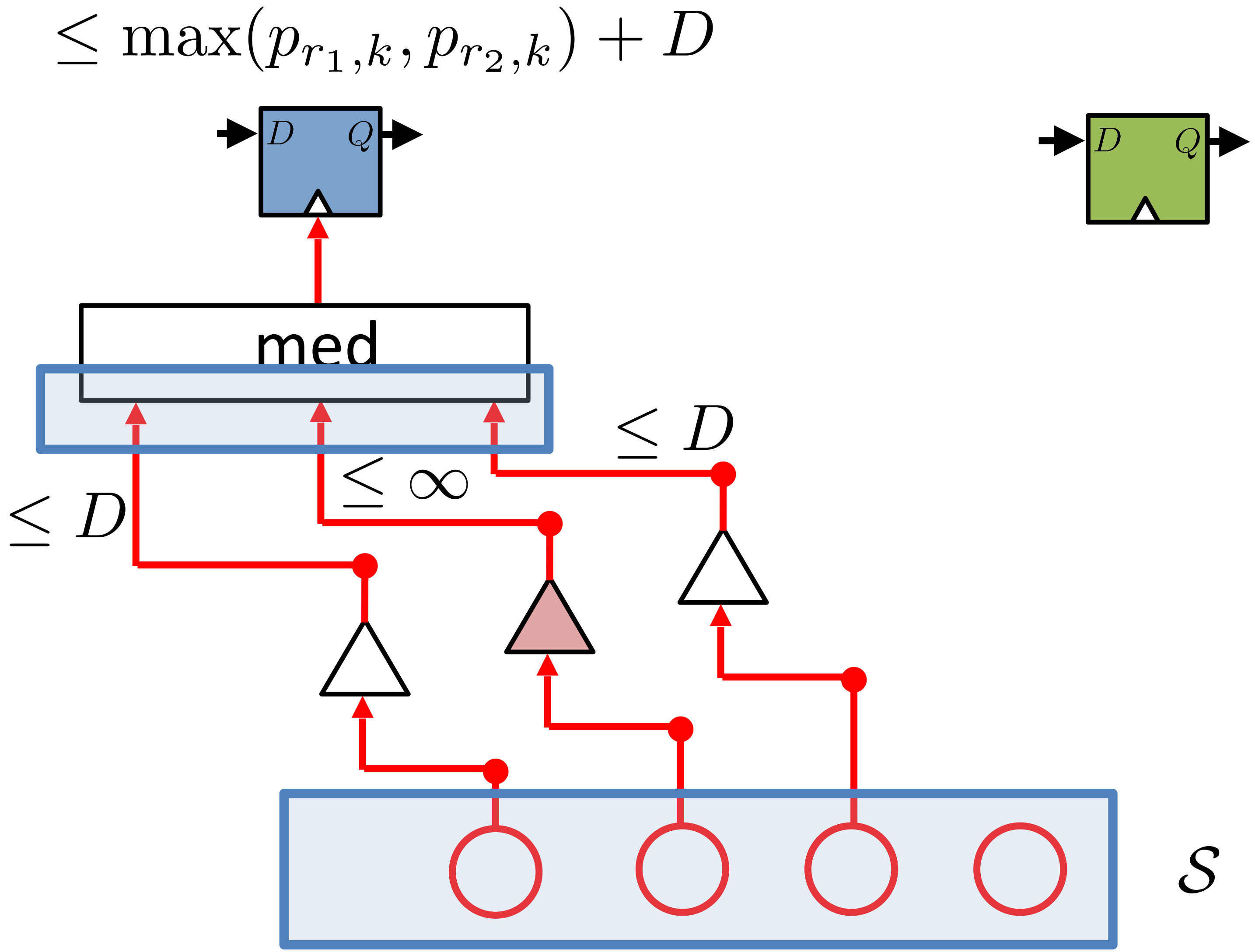


Skew

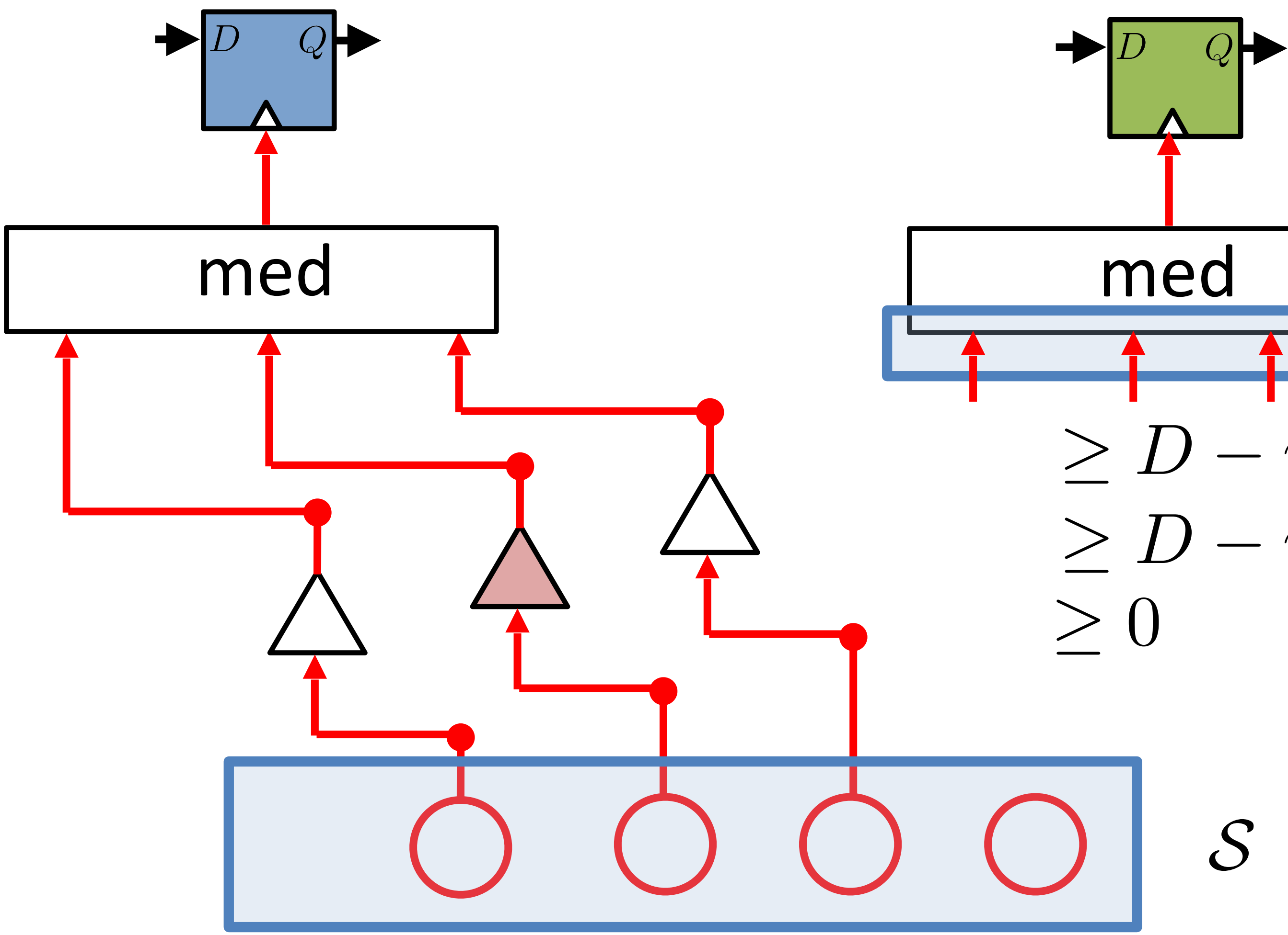


$$
\begin{aligned}
\mathrm{med}(p_{v_1,k}, p_{v_2,k}, p_{v_3,k}) &\leq \mathrm{med}(p_{r_1,k} + D, p_{r_2,k} + D, \infty) \\
&\leq \max(p_{r_1,k} + D, p_{r_2,k} + D) \\
&\leq \max(p_{r_1,k}, p_{r_2,k}) + D
\end{aligned}
$$

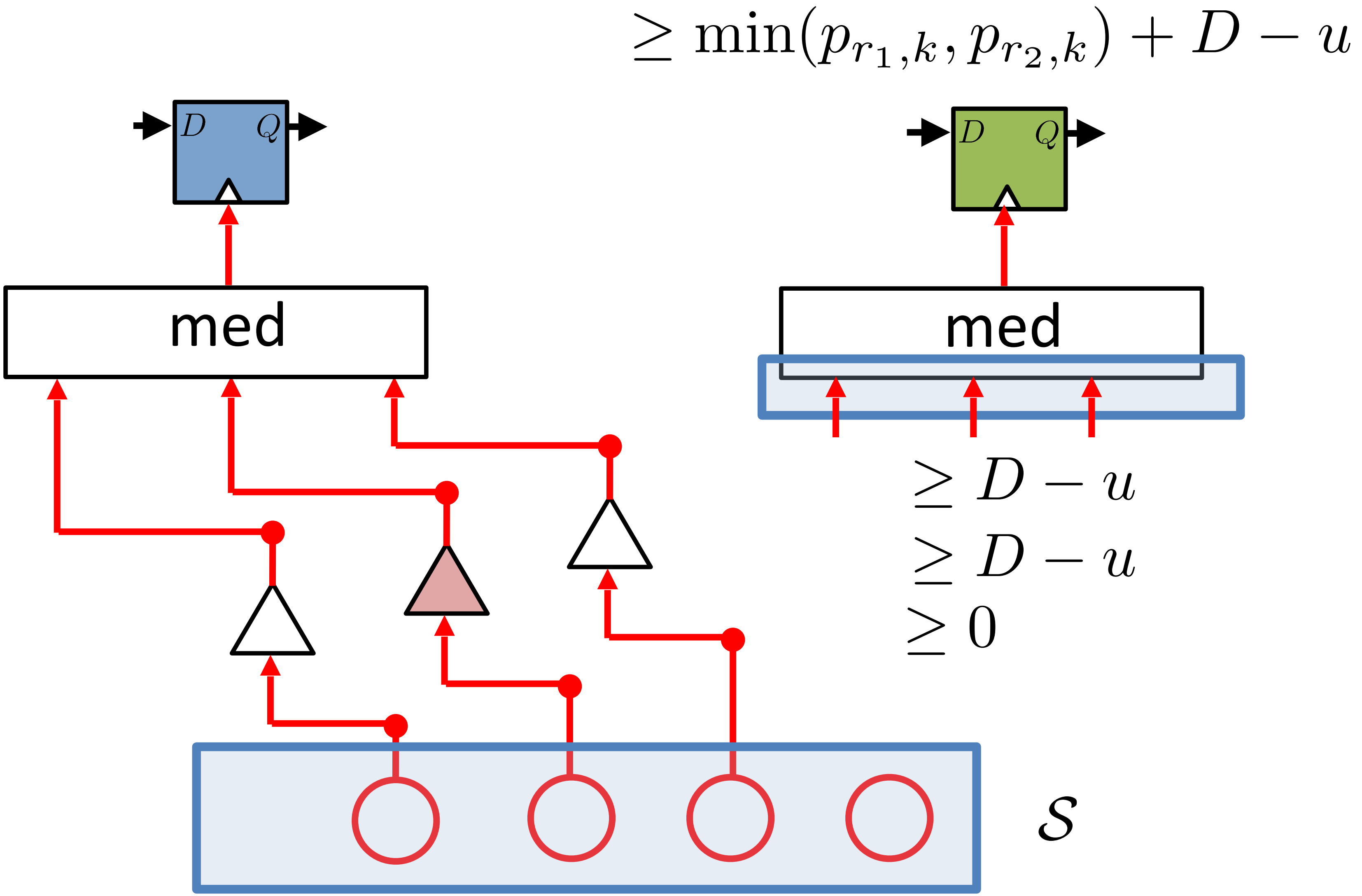
Skew



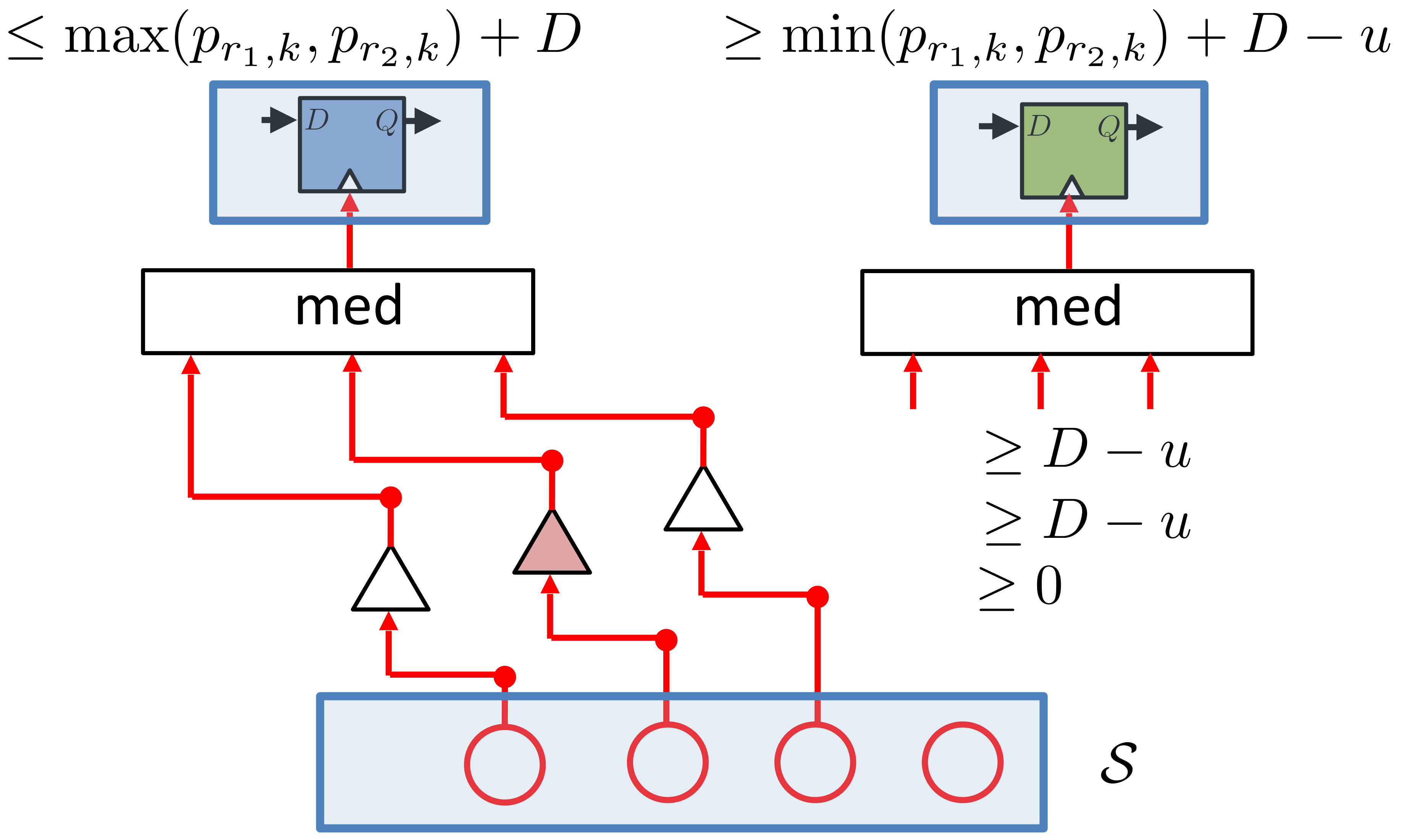
Skew



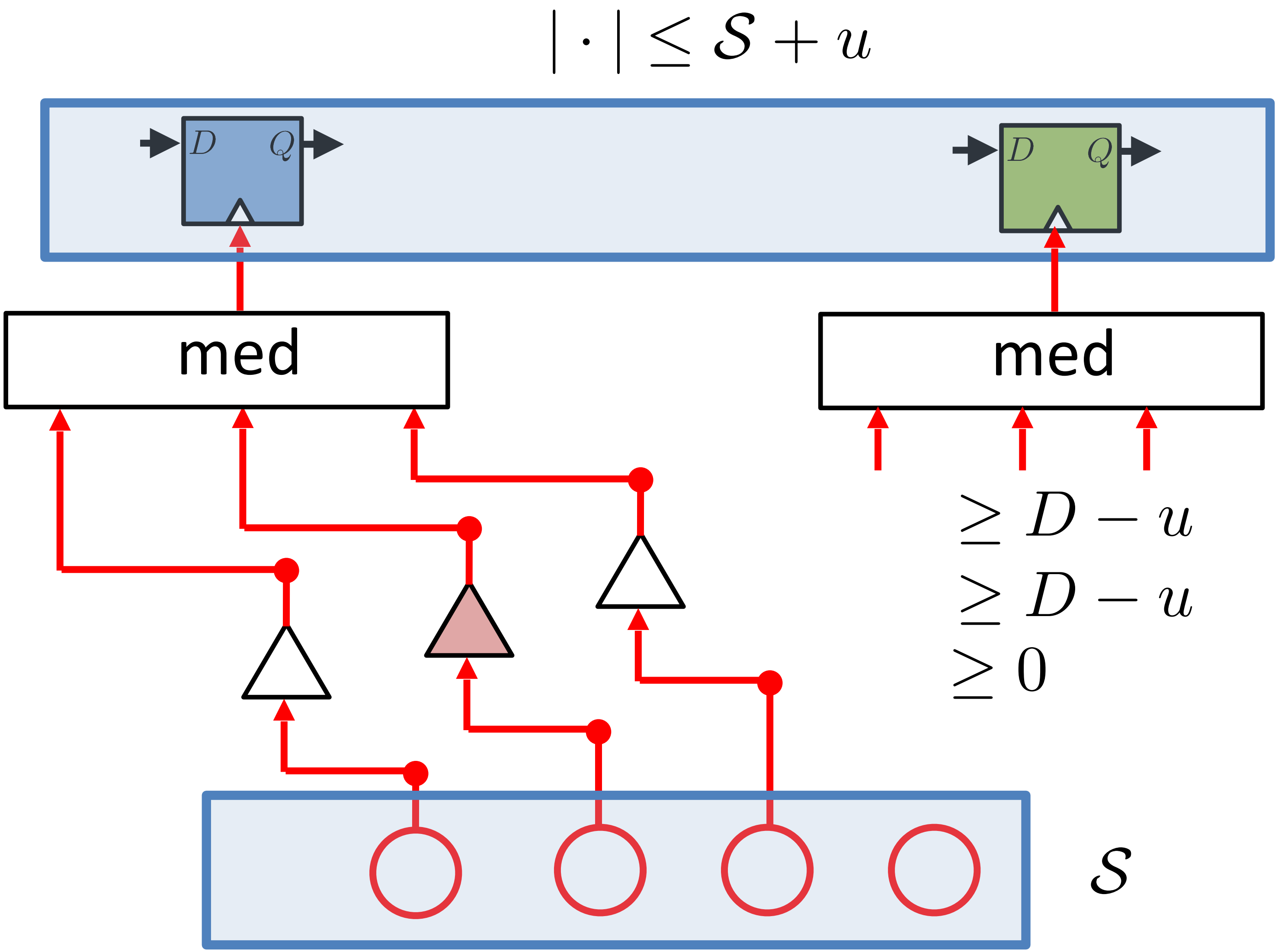
Skew



Skew

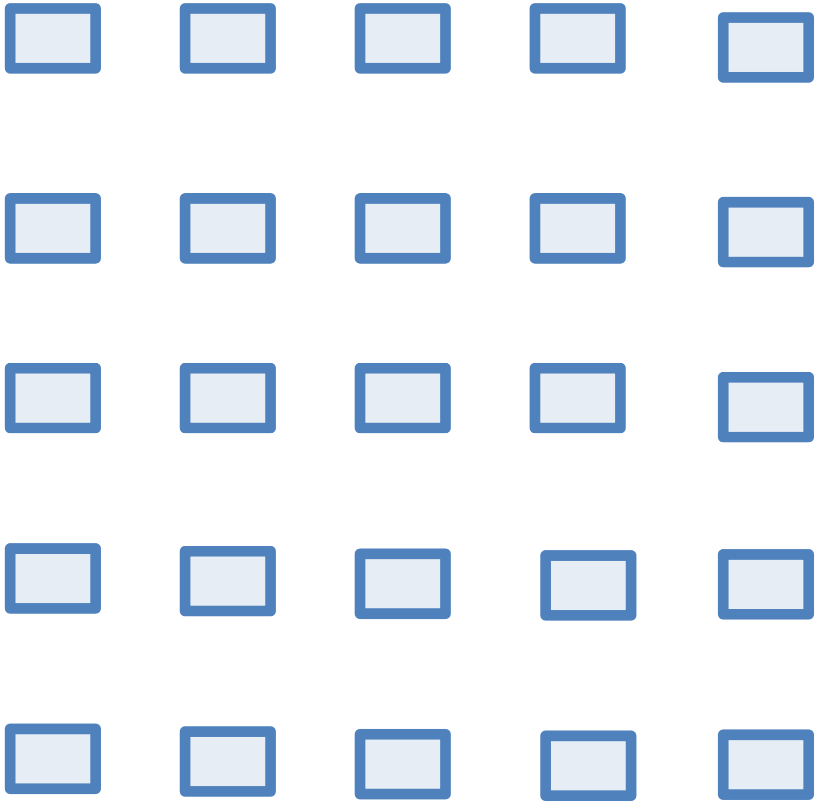

$\leq \max(p_{r_1,k}, p_{r_2,k}) + D$
$\geq \min(p_{r_1,k}, p_{r_2,k}) + D - u$
D
Q
D
Q
med
med
$\geq D - u$
$\geq D - u$
≥ 0
$\mathcal{S}$

Skew



Idea 2

5x5 grid

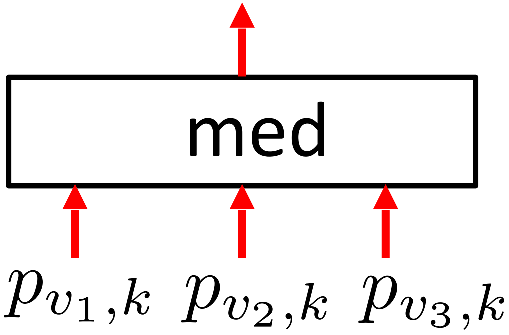


properties:

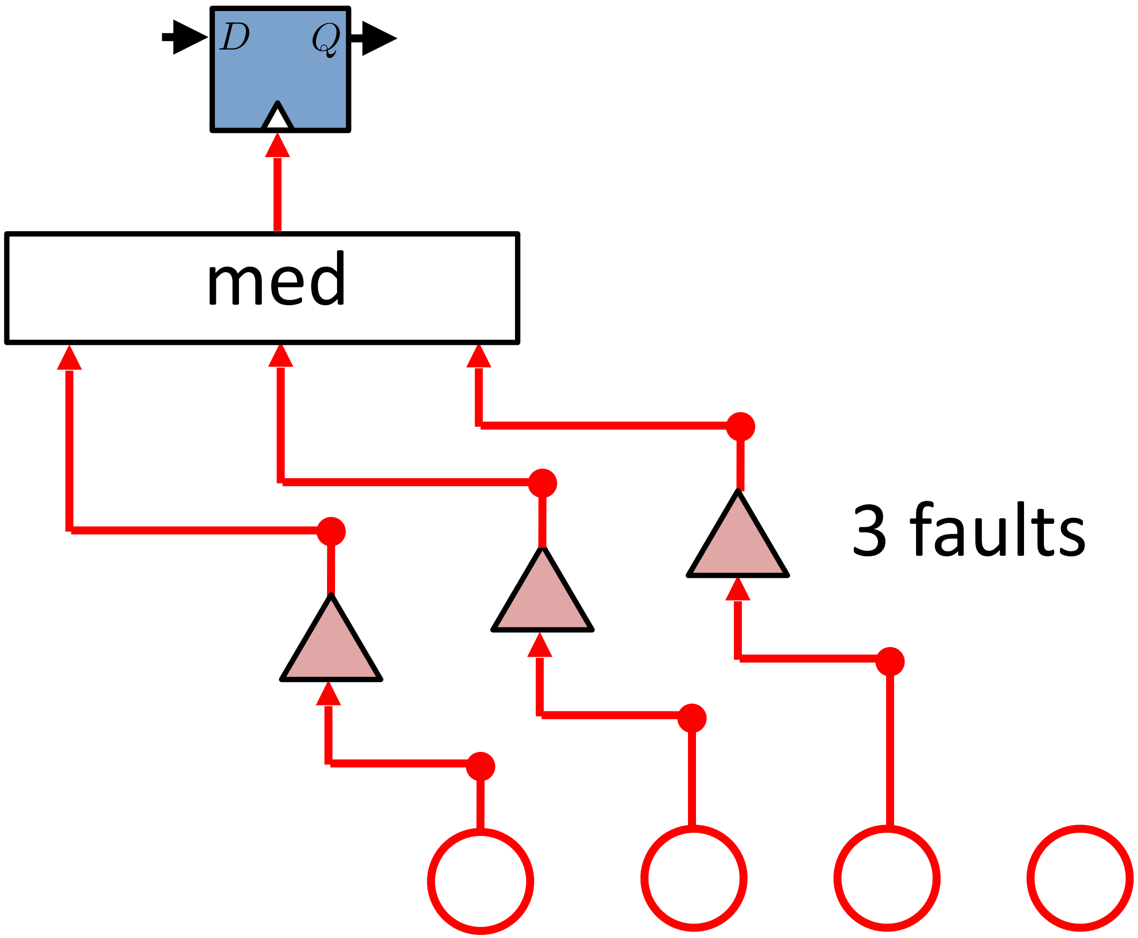
- fault tolerance?
- skew?
- **cost?**

Cost

3f+1 roots & 2f+1 trees



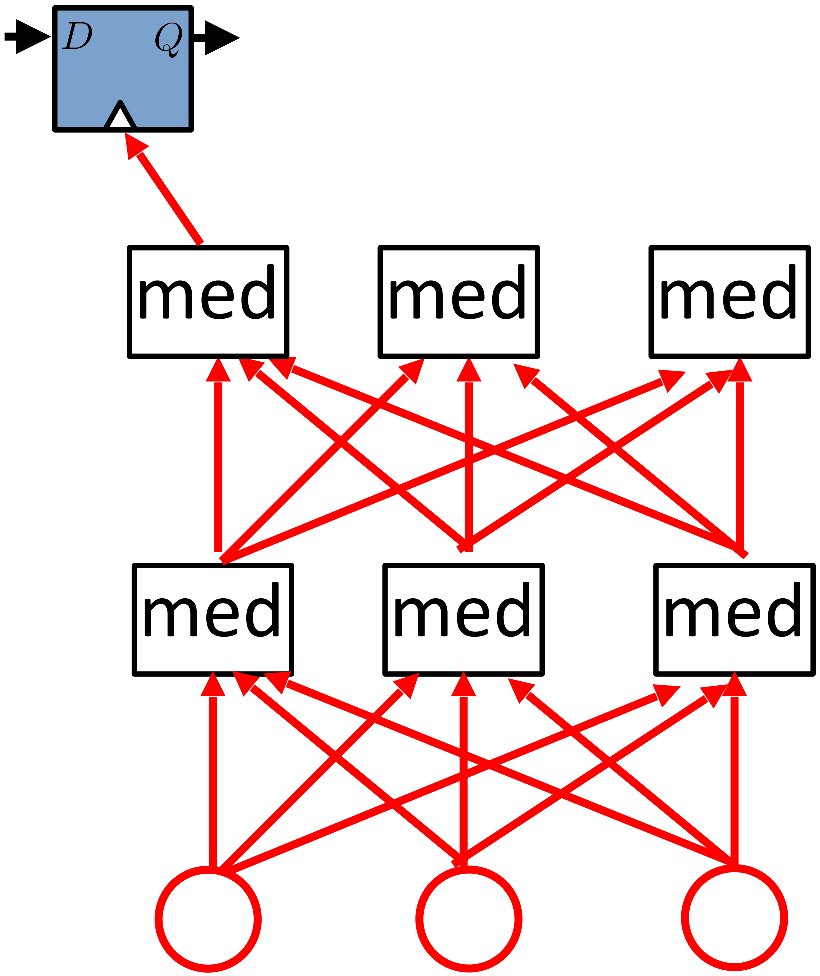
Depends on the environment



Q: other solutions?

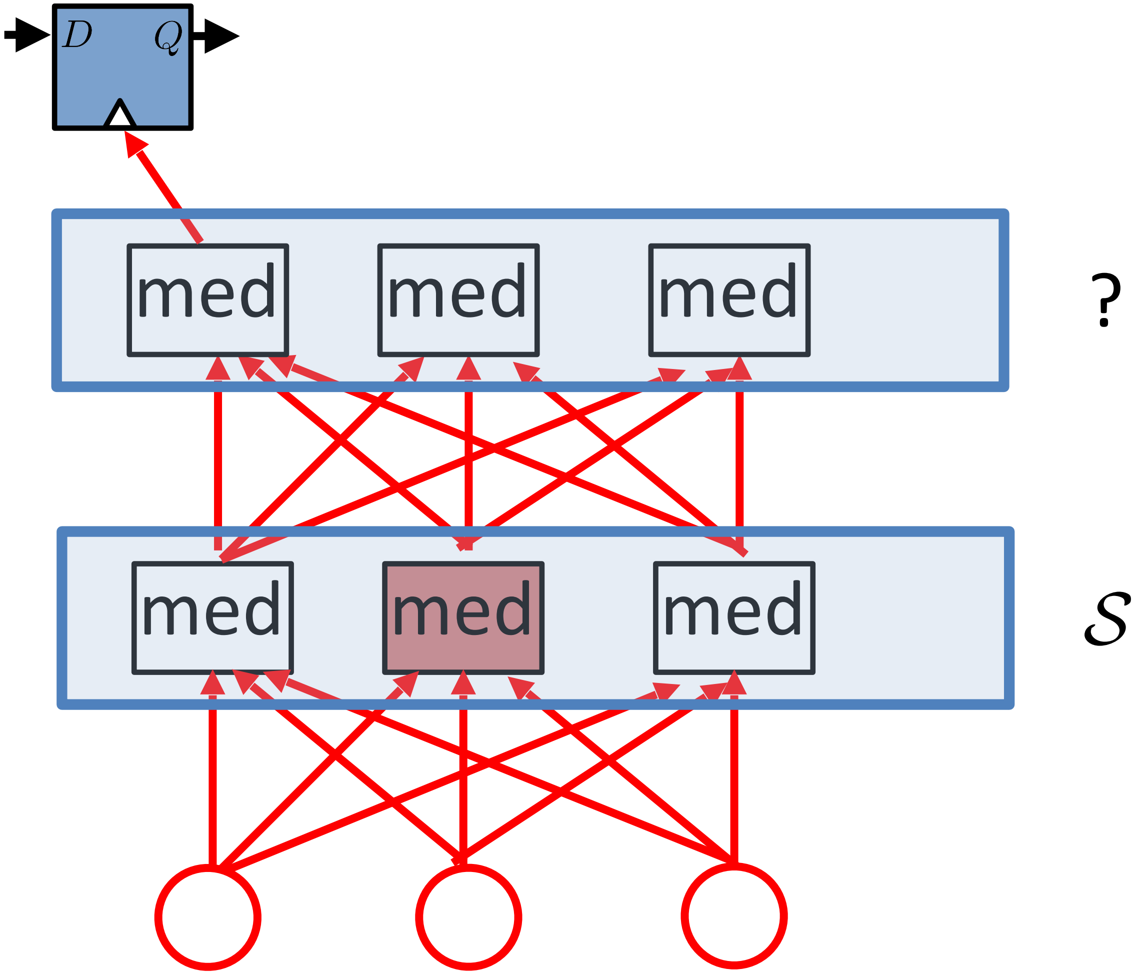
Idea 3: interlinked trees

median at each stage of the tree



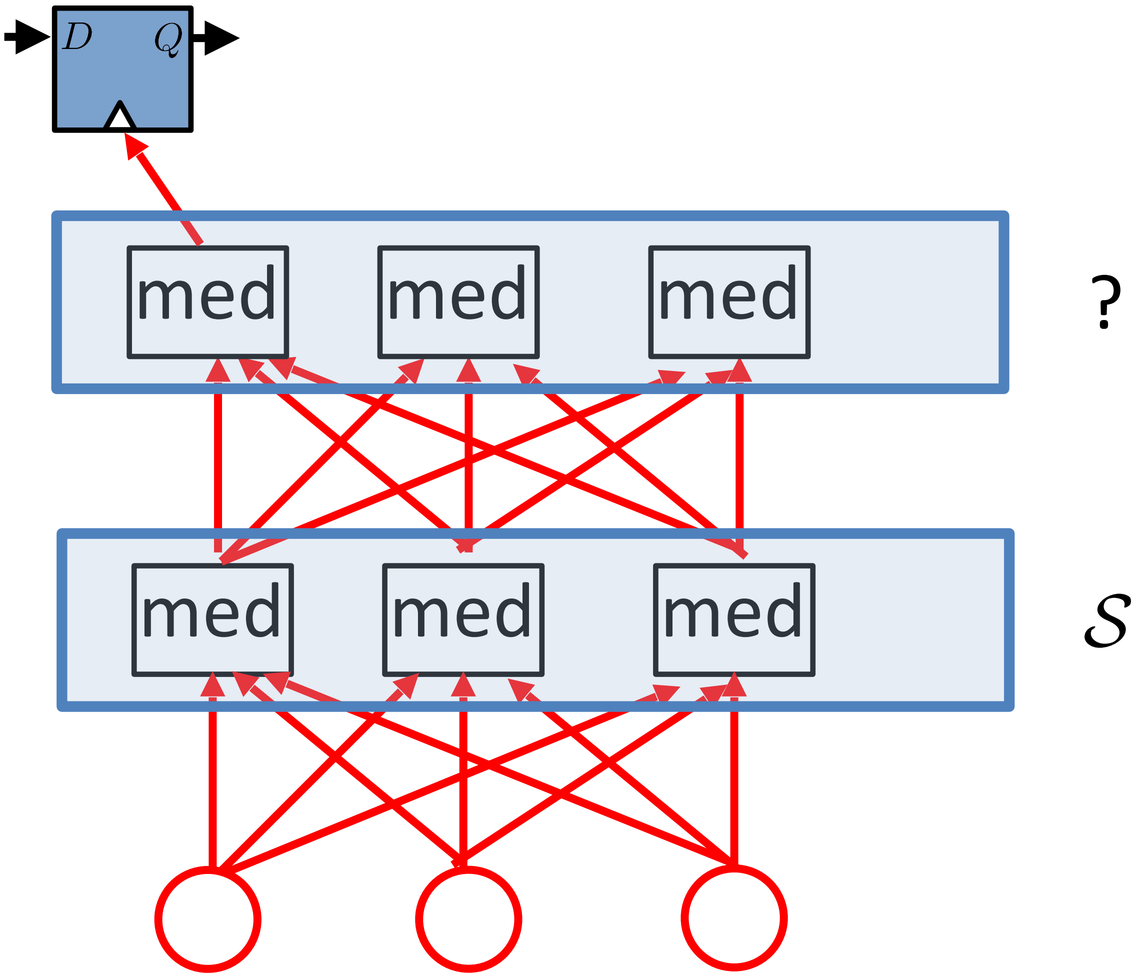
Skew

median at each stage of the tree



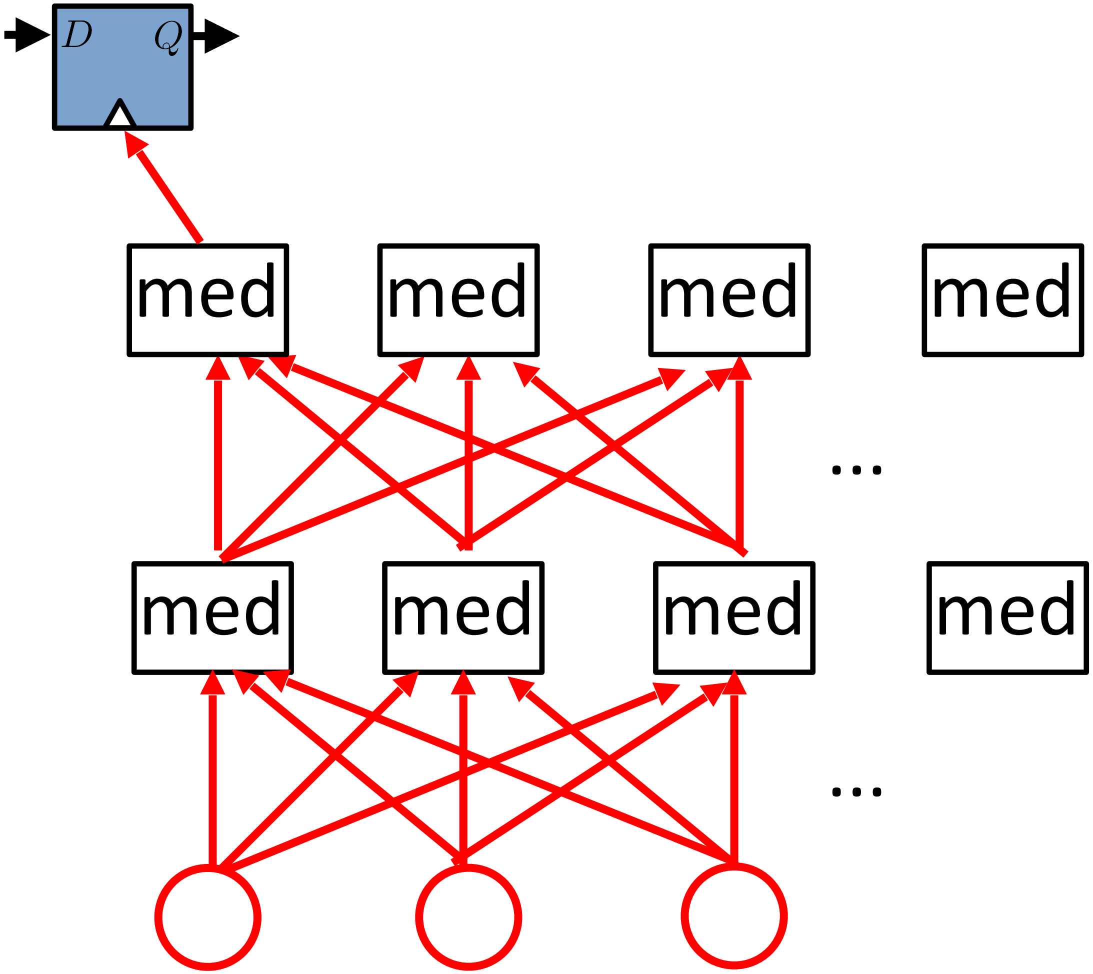
Skew

median at each stage of the tree



Idea 4: interlinked trees v2

median at each stage of the tree



Ex 11.1

$$P(\geq 2 \text{ faults}) = 1 - P(\leq 1 \text{ faults}) \approx 0.80$$

$$1 - \sum_{i=0}^{1} \binom{300}{i} p^i (1-p)^{300-i} \text{ where } p = 0.01$$

$$P(\geq 100 \text{ faults}) = 1 - P(\leq 99 \text{ faults}) \approx 6.9 \cdot 10^{-15}$$

$$1 - \sum_{i=0}^{99} \binom{300}{i} p^i (1-p)^{300-i} \text{ where } p = 0.01$$

100 faults

global constraint (idea 1, LW):

$$P(\geq 100 \text{ faults}) = 1 - P(\leq 99 \text{ faults}) \approx 6.9 \cdot 10^{-15}$$

local constraints (idea 2, redundant trees):

$$P(\text{correct}) = P(\leq 1 \text{ faulty tree})$$

$$\{p = 0.01,\, c = (1-p)^{100},\, c^3 + 3\,c\,(1-c)^2\}$$

$$c\,(4\,c^2 - 6\,c + 3) \approx 0.490383$$

local constraints (idea 3, interlinked trees):

$$P(\text{correct}) = P(\leq 1 \text{ fault per triple})$$

$$\{p = 0.01,\, c = (1-p)^3 + 3\,(1-p)^2\,p,\, c^{100}\} \qquad c^{100} \approx 0.970635$$